Assessment of lateral erosion in three agriculture-dominated Minnesota streams: measurement tools, and factors affecting erosion rates

A THESIS
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Dedications

I would like to dedicate this to those who supported and encouraged me throughout my education: my family and friends; my advisors and professors; and CCCC. I owe you my gratitude.

Abstract

Statewide, 14 percent of Minnesota's impaired waters are listed for excessive turbidity. In-channel and near-channel erosion are commonly considered major contributors to Midwestern turbidity problems. This research sought to determine the primary drivers of channel erosion in the Elm Creek, Buffalo River and Whitewater River watersheds, with a goal of informing guidance and policy on in-channel and near-channel erosion control practices. Of special interest was whether a woody- or herbaceous-dominated riparian corridor was more stable.

First, the definitions, history, and some stream erosion variables are explained. The variables were limited to a brief review of the effects of soil, chemistry, vegetation, hydrology and stream size characteristics. The three study watersheds were introduced.

Second, two GIS-based lateral erosion tools (DNR Static Lateral Migration Tool and BBE Dynamic Lateral Migration Tool) and a common field-based methods (BANCS) were compared. The dataset allowed comparison of results from three tools and multiple users on three streams. The DNR Static Lateral Migration Tool was applied to three streams by one user, and to the Whitewater River by a second. The BBE Dynamic Lateral Migration Tool was applied to the Buffalo River by a third user. The BANCS tool was applied to three streams by a group of users, and to the Whitewater River by another group. The reach breaks for the DNR Static Lateral Migration Tool were chosen to allow comparison of erosion rates to reach-specific variables. The reach breaks for the BBE Dynamic Lateral Migration Tool were at set distances. Generally, the erosion rates across all tools, user groups and streams were between 0 and 0.6 meters (0 and 2 feet) per year, though some results were higher. All GIS-based tools and users

returned erosion rates near or under 1.2 meters (4 feet) per year, with maximum BANCS results near 1.8 meters (6 feet) per year or more. The erosion data allowed for customization of a stream bank erosion prediction graph for comparable Minnesota streams.

Third, using GIS, the lateral erosion rates of nearly 240 reaches of the three streams were compared to other stream characteristics. These characteristics included vegetation type, eroded area, reach length, valley length, sinuosity, water surface slope, low bank slope, high bank slope, water surface elevation, low bank elevation, high bank elevation, low bank height, high bank height, bankfull width, radius of curvature, near bank stress, stream mile (size), curve count, curve length, wetland presence, geomorphology, soils, and erosion to bankfull ratio. Of the measurements available to a GIS-user, near bank stress, and stream size were most correlated to erosion rate in these systems.

Finally, a few of the values associated with Minnesota's water economy are linked to the costs of preventative policy, and reactive restorations. Due to the local need for an accurate picture of erosion drivers and erosion rates, and for an efficient restoration prioritization tool, the University of Minnesota partnered with the Minnesota Department of Agriculture. The work can inform policy and restoration efforts.

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1.1. Introduction

Stream channels are constantly changing. They may change at a slow and predictable rate, keeping their dimensions stable as they erode and deposit sediment, propagating waves of bends or curves that move downstream. They may change more rapidly as a result of land use and channel disturbances, morphing their channel dimensions to accommodate alterations such as more sediment, or more water. Accelerated channel changes, high erosion rates and high sediment loads may indicate an unstable stream.

While some streams are naturally turbid, carrying high levels of sediment, and other light-scattering elements, such as algae, tannins and debris, others are impaired. Through the Clean Water Act, the U.S. Environmental Protection Agency (EPA), and Minnesota Pollution Control Agency (MPCA) have set limits (a water quality standard) on the amount of turbidity an individual stream can maintain without impairing beneficial uses such as drinking water, swimming, fishing, aquatic life, wildlife, navigation, agriculture, and aesthetic enjoyment (MPCA, 2017). Those exceeding the standard are considered impaired, and must be restored through the Total Maximum Daily Load (TMDL) program. Nationally, 55.5 percent of river miles are impaired (EPA, 2016a), with 4 percent of impairments attributed to turbidity (EPA, 2016b).

In Minnesota, approximately 40 percent of assessed waters are impaired (MPCA, 2015a). Of these impaired waters 14 percent (309 lakes and 2142 reaches) are impaired for turbidity (MPCA, 2015c). Specifically, approximately one-third of streams failing to support aquatic life uses have too much total suspended sediment or turbidity (Anderson, 2017). In-channel and near-channel erosion are commonly considered major contributors to Midwestern turbidity problem (Odgaard, 1987; Simon and Rinaldi, 2000, Lenhart et al., 2011).

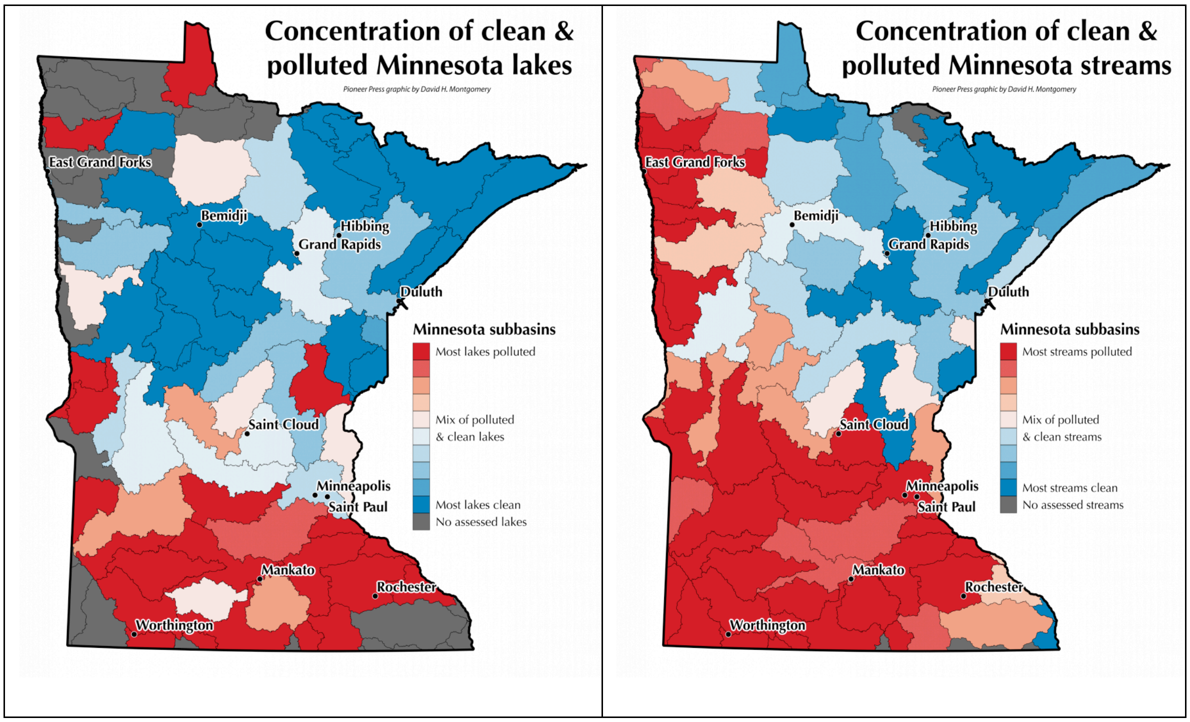

Figure 1: Minnesota's impaired lakes and streams (Montgomery, 2015)

1.1.1. Thesis Outline

This study looks at three streams impaired for turbidity in agriculture-dominated watersheds in Minnesota (Elm Creek, Buffalo River and Whitewater River). Chapter:

1. Briefly reviews the history of channel alterations, channel morphology, and lateral erosion, ending with the hydrological modifications to the three Minnesota streams.
2. Compares two GIS-based lateral erosion tools (DNR Static Lateral Migration Tool, and BBE Dynamic Lateral Migration Tool) and a common field-based method (BANCS).

3. Measures and compares a range of GIS-measurable variables to lateral erosion rates, to determine the primary drivers of channel erosion in the watersheds. Of special interest was whether a woody- or herbaceous-dominated riparian corridor was more stable.
4. Summarizes the first three chapters, with a goal of informing guidance and policy on in-channel and near-channel erosion control practices.
5. Summarizes the thesis and provides the references used throughout the document.

The majority of results from the tools were unitless or in English units. Values throughout the thesis are in "metric (English)" units, and the graphs are in English units.

1.1.2. History of Soil Loss Through Landscape and River Alterations

Americans have a complicated history trying to control streams. As seen below, most early attempts seemed to have unintended consequences, which at the time, where quite surprising. Several programs accomplished exactly the opposite of the intended goal: various flood control projects exacerbated flooding. Throughout the generations, changes to the stream channels and the landscapes surrounding them have accelerated erosion rates, and in some cases, lead to water quality impairments.

In response to demand for easy river navigation, Congress authorized the U.S. Army Corps of Engineers in 1824 and 1866 to clear a path through the Mississippi (USACE, 2008). The Corps removed debris and sediment, narrowing the channels by cutting off access to side channels and installing wing dikes, and dredging the streambed (USACE, 1996; USGS, 2012). In the mid to late 1800s, Congress passed several more acts to drain the nation's wetlands, straighten rivers, and build levees, all believed to control floods (Wohl, 2005). The devastating 1927 Mississippi River flood prompted the 1928 Flood Control Act, making the federal government responsible for flood control in the lower Mississippi River (Simpson et al., 1982). The role of the federal government in flood control grew through successive flood control acts in 1936, 1948, 1954, 1966 and 1970 (Wohl, 2005). It also grew through the New Deal programs of the 1930s, with the Bureau of Reclamation building large reservoirs to supply water to the western United States, the Army Corps of Engineers channelizing and building levees along rivers in the Midwestern and eastern United States, and the Department of Agriculture focusing on flood control and wetland drainage in smaller channels nationwide (Simpson et al., 1982). In the 150 years between 1820 and 1970, more than 330,00 kilometers (205,000 miles) were altered for flood control, agriculture or navigation, 529,912 square kilometers (204,600 square miles) of wetlands were drained (over 65 percent of the upper Mississippi River basin wetlands), and 19 percent of stream miles were inundated by reservoirs (Wohl, 2005).

Suspicious the federal programs were not worth the investment, Congress assigned a task force to study their accomplishments. It noted annual flood damage was $1 billion annually (in 1967 dollars), despite a $7 billion investment in prevention since 1936 (Hunt and Husser, 1988). Removing water quickly from the landscape to the oceans through wetland drainage, stream channelization and levee building, and impounding behind dams was not preventing flooding. When the 1973 congressional report “Stream Channelization: What Federally Financed Draglines and Bulldozers Do to Our Nation's Streams,” and the 1974 Streambank Erosion Control Evaluation and Demonstration Act confirmed suspicions that the nation’s channelization effort was ineffective, the momentum of large-scale hydrologic modification projects waned (Wohl, 2005). The congressional report criticized the nation's affinity for channelizing and ditching, pointing to the fact that those who required, authorized, and implemented the projects rarely knew or attempted to learn the side effects (Wohl, 2005).

The conservation ethic gained momentum throughout the 1900s, with a push from the Dust Bowl Era erosion crisis of the 1930s and failures of hydrologic alteration projects. Knowledge grew through New Deal funding of academic laboratories focusing on erosion, sediment transport and turbulence. Scientists developed the concepts of ecology and ecosystems in the 1940s, and by the 1960s, hydrology and geomorphology were serious fields. Research into stream processes was quickly growing. (Reuss, 2005). Levees lost public support after the 1993 Mississippi River flood (Wohl, 2005). In 2000, the United States government stopped building dams (Wohl, 2005) and generally recognized stream erosion as a major contributor to water quality problems (Lenhart, 2016).

In 1972, landmark legislation was passed to protect water quality. The Clean Water Act requires states to adopt and meet water quality standards. Water quality standards include a designation of a waterbody's use or purpose (such as recreation, drinking water, aquatic life, or industry), and limits on pollutants that would impair a waterbody's ability to serve its designated use.

States develop plans to clean impaired waters. A Total Maximum Daily Load (TMDL) study determines how much pollutant (or load) each point and nonpoint source contribute to the waterbody, before allocating how much each is allowed. This allocation comes with recommendations on achieving the new (if lower) limit of pollution. In the case of sediment loading, it is vital to the accuracy (and ultimately success) of a TMDL to know how much sediment the stream channel itself is contributing.

1.1.3. Stream Evolution

The erosion of a stream channel may be accelerated by land use or channel disturbances. Studies of erosion rates should take this into consideration, by using similarly mature stream reaches. For example, comparing the erosion rate of an herbaceous reach to the erosion rate of a forested reach may be skewed if one reach was recently disturbed and the other was mature. Attributing an erosion rate to one variable may be inaccurate if the stream is also responding to a disturbance. Stream maturity explains the length of time passed since a large channel disturbance, such as a major flood, a major land use change, channelization or damming. A stream adjusting to a disturbance may follow a somewhat predictable pattern to seek out a new equilibrium. Simon and Rinaldi (2006) among others observed the length of time a stream may be adjusting to a past disturbance. They found a sand-bedded system may create a new stable state in 10 to 15 years, whereas silt-dominated systems may take nearly a century (McBride et al., 2010; Simon and Rinaldi, 2006; Yan et al., 2010).

The time elapsed from the last major channel disturbance is therefore an important factor to keep in mind when apportioning the significance of erosion variables; to ask: “Are the variables studied the only reason for this erosion rate, or is the stream also recovering from a disturbance?”

Simon and Rinaldi (2006) listed a number of studies describing the sequential adjustments a stream will make to recover from a disturbance. These included Davis and Sutherland (1902), Ireland et al. (1939), Schumm and Hadley (1957), Daniels (1960), Emerson (1971), Keller (1972), Elliot (1979), Schumm (1984), Simon and Hupp (1986), Simon (1989), and Cluer and Thorne (2014).

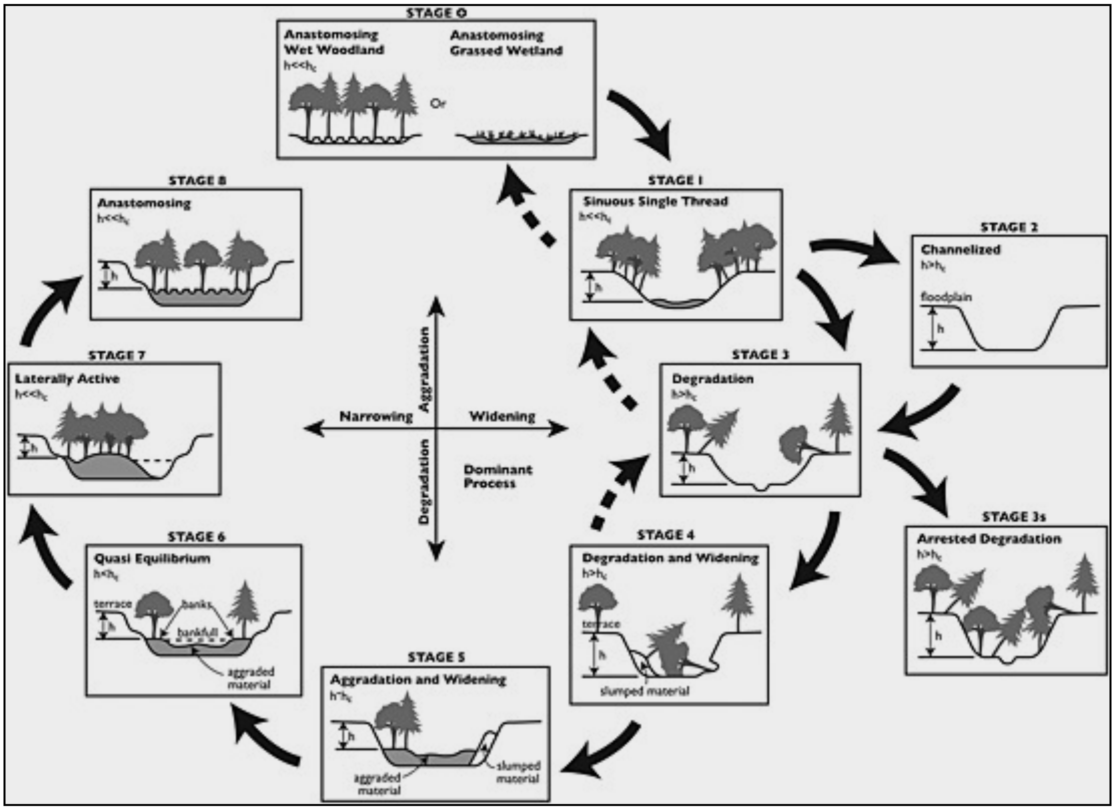

Figure 2: Sample channel evolution model (Cluer and Thorne, 2014)

A commonly cited pattern of stream evolution is the Schumm et al. (1984) Channel Evolution Model, which was subsequently modified by Simon (1989). It describes six sequential forms a river takes as a reaction to a major disturbance: Stage 1 is Premodification (stable state prior to disturbance), Stage 2 is Constructed (dredging, channelization or discharge increase; the disturbance), Stage 3 is Degradation (downcutting or incising), Stage 4 is Threshold (mass wasting), Stage 5 is Aggradation (the channel begins to fill), and Stage 6 is Restabilization (flow can once again overtop banks).

Simon and Rinaldi (2006) went on to describe the stages as an imbalance between stream power and sediment loading. Degradation reduces stream power by flattening bed slopes. This incising generally migrates upstream as sediment loads overpower stream power. Degradation eventually creates such steep and tall banks that the critical shear strength of the banks are exceeded and the next stage is reached. During Threshold, the stream banks begin sloughing and flushing away in mass wasting events and the bed widens. Aggradation occurs when the volume of sediment sloughing from banks and carried in the flow exceeds stream power and begins accumulating. Pioneer species further diminish stream power, accelerating aggradation. Eventually the bed elevates enough to allow the stream to overtop banks into the original, or a modified floodplain, which is a terrace lower (and therefore confined) by its original floodplain. At this point, the stream has reached Restabilization. If the stream did not reach its original floodplain, it may adjust to a narrower floodplain by increasing its length and decreasing its slope by accentuating meanders (Simon and Rinaldi, 2006).

McBride et al. (2008, 2010) founded a similar model describing the transition streams make in response to reforestation. In the beginning, the banks are herbaceous, and the channel is stable, small and easily overtops its banks. As small woody plants sprout and grow, the bank roughness increases, altering floodplain hydraulics by reducing the speed of flood waters outside of the channel. The in-channel flood flow velocity remains the same however, increasing turbulence at this interface and therefore increasing scour. The scour spreads into bed degradation. The channel widens and deepens, sinking away from its floodplain. As the woody plants mature and begin shedding branches or falling entirely into the stream, grasses are outcompeted, and the surcharge (weight) on banks increases. The final, forested product is wider, slower (with more in-stream roughness) and has a richer habitat compared to the grass system (Sweeney et al., 2004; Allmendinger, 2005; McBride et al., 2008, 2010).

1.1.4. Lateral Erosion

Streams react to disturbances and evolve over time by moving vertically and horizontally. A vertical change can indicate a sediment supply imbalance. When a stream has too much sediment to carry, or too much in-channel roughness, it may aggrade, or raise its bed as it deposits sediment (Bull, 1979; Galay, 1983). Conversely, when a stream has too little sediment or too little in-channel roughness to regulate its speed, it may incise, or lower its bed as it scours the channel.

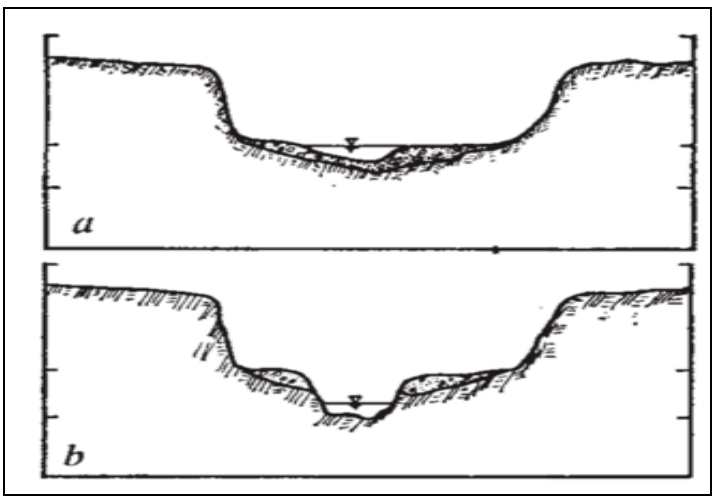

Figure 3: Aggradation and degradation, in (a) and (b), respectively (Schumm and Parker, 1973)

A horizontal change can indicate a variety of disturbances or processes. The category includes avulsion, channel width changes, and lateral movement (WSDOE and WSDOT, 2003). An avulsion is a sudden course change, which can be triggered by a flood establishing a new channel, or a meander bend cutoff. A channel may widen or narrow in response to a change in vegetation, sediment supply or hydrology (WSDOE and WSDOT, 2003). Variables influencing lateral channel movement will be explored in this and following chapters. The category includes meander bend development, flow diversion, and increased erodibility (WSDOE and WSDOT, 2003).

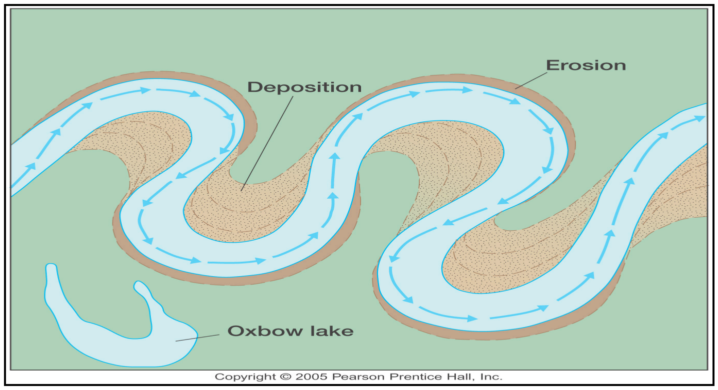

Figure 4: Lateral migration (GCCAZ, 2017)

Generally, lateral erosion occurs when the laterally sloping bed near an outside bank is scoured by fluvial erosion, the unsupported portion falls in a mass failure event, and the resulting debris is swept downstream before the process repeats (Thorne, 1990; Burkhardt and Todd, 1998; Nanson and Hickin, 1986; Simon and Collison 2002). Lateral erosion focuses on bank retreat, without necessarily accounting for sediment deposition. Lateral migration includes deposition: the inside curve receives sediment deposits, which are colonized by riparian vegetation, allowing the inside curve to slowly chase the receding bank (Burckhardt and Todd, 1998). Rivers can move dramatic distances laterally, leaving spectacular displays of relict and active looping pathways across a landscape.

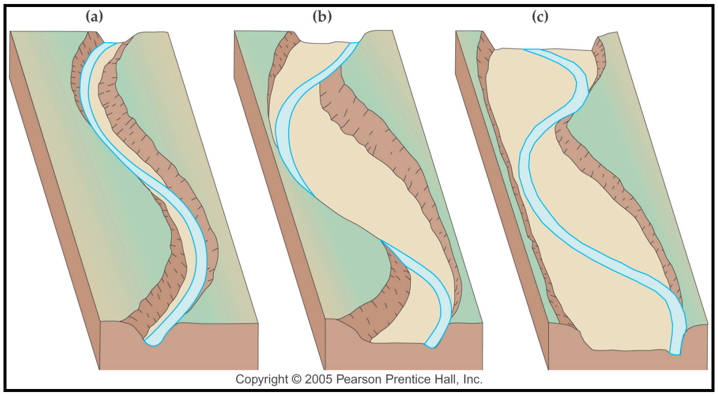

Figure 5: Lateral erosion (GCCAZ, 2017)

1.2. Factors Influencing Lateral Erosion Rates: Soil, Chemistry, Vegetation, Hydrology and Stream Size

Far too many studies to cite have credited an exhaustive array of variables with a role in lateral erosion, each study claiming a single or combination of factors being the most responsible for erosion. Lists can include the soil/geology factors such as bulk density, cohesion, texture, sheer and tensile strength, permeability, stratigraphy, bank height, freeze-thaw, desiccation, and the like; vegetation factors such as rooting depth, rooting density, interception, insulation from freeze-thaw and desiccation, channel and floodplain roughness, windthrow, local groundwater level, and the like; and hydrology factors such as discharge, catchment area, stream power, slope, sinuosity, precipitation, sediment transport, sheer stress, and the like. As Osterkamp and Hupp (2010) pointed out, cataloging the responsible factors is challenging because most are interdependent. This study is broken into five generalized categories: the characteristics and processes associated with soil, chemistry, vegetation, hydrology and stream size. The interconnectedness of these stream features creates inevitable overlap between the categories.

1.2.1. Influence of Soil and Chemistry on Erosion Rates

Soil in and of itself can provide some stability of a bank against erosion. Soil bulk density can be used as a surrogate for soil erodibility and critical shear stress; and may be the most significant factor influencing bank erosion (Bouyoucos, 1935; Glinski and Lipiec, 1990; Dunaway et al., 1994, Wynn and Mostaghimi, 2006a). The soils with smaller pore spaces, due to presence of silt and clay, are less likely to become dislodged; and higher bulk density soils are less erosion-prone (Hooke, 1979; Mosselman, 1992; Abernathy and Rutherfurd, 1998; Wynn and Mostaghimi, 2006a; Wynn and Mostaghimi, 2006b; Sass and Keane, 2012). Nanson and Hickin (1986) found 70 percent of bank erosion in a sand-gravel system was due to stream and sediment size.

Matric suction and pore-water pressure are intrinsic soil properties (Simon and Collison, 2002). Soil is assumed to be least cohesive after prolonged wet periods (Abernathy and Rutherfurd, 1998). In over-simplified terms, soil that is too wet or too dry is more prone to erosion. Many factors influence the ideal moisture level for maximum cohesion, including a soil's sand, silt and clay composition, compaction and profile. Many other factors influence when soil is at that ideal moisture, including weather, ground cover, roots, and groundwater depth. This would explain some of the variability in studies. Simon and Pollen (2006) found generally increasing bank stability as the soils dried; as the matric suction, or negative pore-water pressure increased. Conversely, Wynn and Mostaghimi (2006a) found increasing bank stability as moisture levels increased in sandy soils.

A common phrase states soil is strong in compression but weak in tension, while roots are the opposite: strong in tension, but weak in compression (Thorne, 1990; Wynn and Mostaghimi, 2006a; Pollen, 2007). The combination of soil and root networks therefore complement each other, creating a much stronger material (Thorne, 1990; Wynn and Mostaghimi, 2006a; Pollen, 2007). Soil has the ability to limit rooting depth and density, thereby limiting the benefits of this partnership. Dense soils, with higher clay and silt content, have been found to limit rooting depth and density (Dunaway et al., 1994; Crow, 2005), whereas loose, sandy soils tend to facilitate deeper and thicker rooting networks (Dunaway et al., 1994). There is a positive correlation between increasing soil bulk density, and decreasing moisture and nutrient availability, and consequently decreasing root growth and density (Andrews and Newman, 1970; Kramer, 1983; Glinski and Lipiec, 1990; Dunaway et al., 1994). Not every study found a correlation between soil bulk density and root density, however. Underhill (2013) found no correlation between the two, perhaps due to a predominance of loamy soil, or lack of soil compaction.

The size of soil particles has also been linked to a root's ability to resist removal. Despite potentially occurring less frequently in denser soils, the small particle sizes provides more surface area for fine roots to grasp, thereby providing another mechanism to decrease erosion (Wynn and Mostaghimi, 2006a).

Wynn and Mostaghimi (2006a) found fluvial erosion rates were closely tied to stream water chemistry and soil chemistry. The chemistry suite of interest to Wynn and Mostaghimi (2006a) was pH, specific electrical conductivity, pore water salt concentration, potassium intensity factor, and sodium adsorption ratio. These variables can be influenced by precipitation events, road salts, and rapid vegetation growth and decay (Wynn and Mostaghimi, 2006a; Osterkamp and Hupp, 2010). In general, higher pH (and therefore higher cation exchange capacity) soils, with lower salt concentration (Wynn and Mostaghimi, 2006a) are more prone to erosion. The types of soil most likely to be affected by cation exchange capacity and pH are clays and soils with high organic matter content; these soils are most susceptible to dispersion due to surface charge repulsion (Grissinger 1982; McBride, 1994).

1.2.3. Influence of Vegetation on Erosion Rates

The relationship between hydrology and bank stability is complicated by roots. Soil that is too wet or too dry may contribute to erosion. The soil moisture content impacts the stability of soil, groundwater influences the rooting pattern of vegetation, and roots influence soil moisture.

Roots need oxygen and nutrients to thrive, neither of which is available in abundance below the level of groundwater (McGinty, 1976; Gray and Leiser, 1982; Coppin and Richards, 1990). Numerous studies find riparian root systems are generally limited to approximately 1 meter (3.3 feet) in depth (Davidson et al., 1991; Shields and Gray, 1992; Jackson et al., 1996; Sun et al., 1997; Abernathy and Rutherfurd, 1998; Tufekcioglu et al., 1999; Simon and Collison, 2002; Wynn et al., 2004; Pollen, 2004; Underhill, 2013; UMN, 2015). Variability in this number can be due to soil type, groundwater level, and plant species. Below 1 meter (3.3 feet), root networks may be much less beneficial to bank stability. With the erosive forces of streams so often scouring below this rooting depth (Abernathy and Rutherfurd, 1998) or within saturated zones, Pollen (2007) states roots may provide the least reinforcement when a bank is most at risk of failure, such as the receding limb of a hydrograph.

For example, Abernathy and Rutherfurd (1998) found a direct correlation between windthrow (trees blown into streams) and high groundwater levels. Abernathy and Rutherfurd (1998) applied this, finding that trees in the headwaters were more likely to be blown into channels due to a shorter distance between soil surface and groundwater. By providing as little as 0.6 meters (2 feet) of additional clearance to groundwater, taller banks allowed trees to resist windthrow (Abernathy and Rutherfurd, 1998). Windthrow is seen by many to be a major contributor to bank erosion (Jeffries et al., 2003; Allmendinger et al., 2005; Montgomery, 1997; Murgatroyd and Ternan, 1983; Trimble, 1997; Brummer, 2006). The roots of those trees, and other vegetation, in turn, are a determining factor in soil moisture.

Pollen (2007) observed root reinforcement was minimal when the soil moisture was highest. If banks are viewed as more stable when drier (within reason), then vegetation benefits them hydrologically through canopy interception and transpiration (Pollen, 2007). Canopies shelter the soil from precipitation, while roots remove water through matric suction. A small, forested stream could maximize hydrologic benefits by deflecting the most rainfall with its canopy, and removing the most groundwater due to short banks (short distance from surface to saturation) (Burkart et al., 2004).

Vegetation can also be a detriment, however, when canopy interception and stemflow concentrates rainfall and increases infiltration, creating locally higher moisture, and pore-water pressure. When soil is wet, pore-water pressure is higher, and soil cohesiveness is lower (Underhill, 2013). The model by Collison and Anderson (1996) found the increased infiltration and preferential flow induced by vegetation could create a hydrologic effect sufficient to outweigh mechanical benefits of rooting patterns.

Mechanical benefits of vegetation include rooting strength, buttressing, and weight (Simon and Pollen, 2002; Pollen, 2007).

Pollen (2007) found a threshold root diameter, at which all roots broke, rather than responding to stress with a combination of breakage and pullout. The threshold depended on soil shear strength, and matric suction. Root breaking was most common in dry soils (when shear strength was higher), while pullout was more common in moist soils (when shear strength was lower). Additionally, small roots were likely to pull out of the soil, whereas large roots were prone to breaking. Camporeale et al. (2013) found the tensile strength of most species to fall between 10 and 40 MPa (1,450 to 5,802 psi).

More studies linking vegetation and erosion rates will be reviewed in Chapter 3, including vegetation's ability to buffer soils from the erosive effects of freeze-thaw and wet-dry cycles, vegetation's role in sediment loads, a comparison of the different patterns of roots and erosion, the effect of added floodplain roughness (vegetation) on flood responses, vegetation types and channel width, the influence of large woody debris on different channel sizes, and an overall comparison of woody versus herbaceous species on erosion rates.

1.2.4. Influence of Hydrology on Erosion Rates

The timing (season, frequency and duration) as well as size of hydrologic events can be quite influential on streambank stability. A stream's reaction to a precipitation or snowmelt event can be plotted as a generally bell-shaped hydrograph. The rising limb of a hydrograph indicates an influx of water, the top of the curve represents the peak flow, and the receding limb shows the flow returning to normal. Researchers have compared erosion rates to the timing and size of hydrologic events.

The seasonal component of erosion-induced hydrologic events is commonly tied to the absence of biological activity. For a period of the year, interception and transpiration are minimal, when deciduous canopies are gone, herbaceous cover is dead or dormant, crops are harvested, and root density is lower (Simon and Collison, 2002; Wynn et al., 2004). Snow melting and rain falling under these conditions is especially effective at dislodging sediment and eroding landscapes. Simon and Collison (2002) found two-thirds of rain fell while canopy cover was absent between October and April. MPCA (2012b) found the highest turbidity values in Minnesota was associated with spring snowmelt and heavy spring rains, and concluded coverage provided by crops and natural vegetation significantly reduced erosion.

The speed at which a stream reacts to increasing and decreasing flows can be tied to erosion rates. Hooke (1979) compared discharge, rainfall and soil moisture variables to erosion rates. The study found correlations to peak discharge, and the speed at which flows swell in response to increased water supply. Of all variables considered, the rising limb of the hydrograph was highly ranked in relation to maximum erosion and proportion of bank eroded, though interrelated to other factors (Hooke, 1979). Lawler (1997) and Zaimes (2015) found the receding limb of the hydrograph correlated with mass erosion events. Overall, very little erosion occurred without a peak flow, regardless of the size of the rain event; and erosion was most driven by the speed at which a discharge increased (rate of hydrograph rise) (Hooke, 1979).

The frequency of channel-forming flows, and larger volume events can influence how much sediment a channel carries. Zaimes et al. (2006) found the highest erosion rates correlated to closely spaced medium and large precipitation events in spring and early summer. Later in the year, canopy cover and evapotranspiration diminished the correlation between precipitation and erosion.

While bankfull has a recurrence interval of one to two years, and is credited as the dominant channel-forming flow (Leopold et al., 1992), larger and less frequent flows are important to bank erosion rates.   Floods are by nature quite erosive (Rood et al., 2014), control riparian vegetation patterns (Camporeale et al., 2013) and are becoming more frequent (Mallakpour and Villarini, 2015). Not all high water situations are erosive, however. Abernathy and Rutherfurd (1998) among others, have explained that the hydrostatic pressure a flow exerts on a bank can recharge floodplain groundwater levels, and therefore resist mass failure.

1.2.5. Influence of Stream Size on Erosion Rate and Erosion Type

Some have named stream size as a major determiner of bank erosion rate. For example, Nanson and Hickin (1986) found 70 percent of the soil volume lost from outer meander banks of large sand-gravel streams was explained by stream and sediment size. These two factors, Nanson and Hickin (1986) points out, are essential components of, and therefore inform sediment entrainment.

Others have used river size to describe the type of erosion. Lawler (1992, 1995) is credited with creation of a popular three-part explanation of erosion types: subaerial preparation, fluvial erosion, and bank failure. Many publications reference it in describing erosion along stream systems.

Subaerial preparation is the hardest to define. It includes a broad range of climate- and vegetation-related processes, such as freeze-thaw cycling, wet-dry cycling, windthrown trees, rainsplash, micro-rill erosion and damming by large woody debris

(Lawler, 1995; Abernathy and Rutherfurd, 1998; Wynn and Mostaghimi, 2006a; Wynn and Mostaghimi, 2006b; Camporeale et al., 2013; Underhill, 2013, Zaimes and Schultz, 2015). While subaerial preparation does provide sediment to a stream, it is generally seen as conditioning a bank for a larger erosion event. A number of studies find subaerial processes dominate small headwater streams (Lawler, 1995; Abernathy and Rutherfurd, 1998; Wynn and Mostaghimi, 2006a; Burkart et al., 2004; Camporeale et al., 2013; Underhill, 2013). This type of erosion is only apparent in areas with wide temperature and precipitation swings, or where the other two processes are limited (Thorne, 1982; Wynn, 2005). This can be seen when topsoil accumulates lower down the bank profile.

Fluvial erosion is typically seen as dominating the moderately-sized or middle sections of streams (Lawler, 1995; Abernathy and Rutherfurd, 1998; Wynn and Mostaghimi, 2006a; Burkart et al., 2004; Camporeale et al., 2013; Underhill, 2013). Fluvial erosion is the direct removal of soil by water flowing through the channel. This includes channel and bank scouring. In these sections, subaerial preparation is not as pronounced due to larger channel size and bank heights. For example, in-channel large woody debris may be swept away by higher discharges, the larger distance between the soil surface and groundwater allows trees and plants to grow denser, with deeper roots, aiding in resistance to temperature- and moisture-related damage by insulating soil and withdrawing more soil moisture, as well as windthrow (Abernathy and Rutherfurd, 1998; Underhill, 2013; Crow, 2005). This can be seen when erosion occurs during the rising limb of a hydrograph (Lawler, 1997).

Bank (or mass) failure is generally cited as the dominant erosion category on large, or lower stream reaches (Lawler, 1995; Abernathy and Rutherfurd, 1998; Wynn and Mostaghimi, 2006a; Burkart et al., 2004; Camporeale et al., 2013; Underhill, 2013). These occur when the shear strength of the soil (soil cohesion augmented by roots, but undercut by scour) is overpowered by its own weight, and the weight atop the soil. This can be seen when erosion occurs as a hydrograph falls (Simon, 2000).

1.3. Influencing Impairments in Minnesota: Watershed Development

As prairies, wetlands and forests became farms and cities, Minnesota streams adjusted to the new sediment and water levels associated with altered perviousness, storage and evapotranspiration. Streams also adjusted to direct channel alterations such as dredging, channelization, burial, expansion of watershed through ditches and pipes, and other alterations for watershed development.

Some of these alterations, and subsequent adjustments increased turbidity levels past water quality standards, triggering impairment status and TMDL studies. Watershed development is a common stream stressor, and was assessed as a possible cause of impairment during the TMDL process for Elm Creek, Buffalo River and Whitewater River (MPCA, 2015).

1.3.1. Study Area

Elm Creek, Buffalo River and Whitewater River are the subject of this research. Each is located in an agriculture-dominated watershed, representing different ecoregions of Minnesota: Elm Creek is in south-central Minnesota’s prairie pothole region and Western Corn Belt Plains, the Buffalo River is in western Minnesota’s Glacial Lake Agassiz and Central Hardwood Forest, and the Whitewater River is in southeastern Minnesota’s Driftless Area along the Mississippi River bluff.

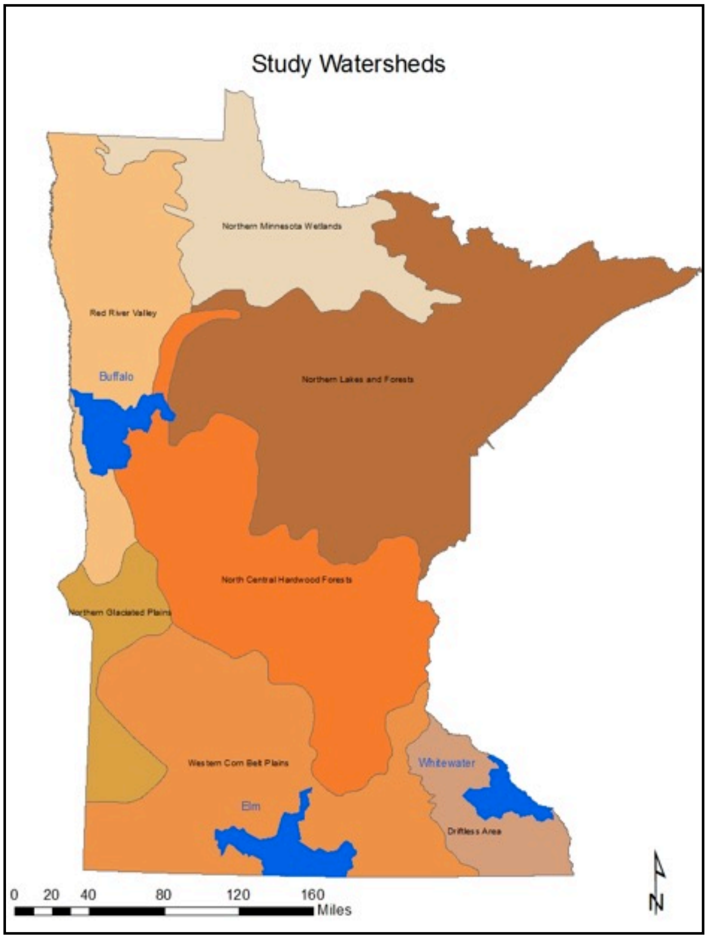

Figure 6: Study watersheds in blue on Minnesota ecoregions in shades of brown

1.3.2. Hydrologic Storage and Altered Watercourses

In the loess region of the Midwestern United States, Simon and Rinaldi (2006) found most tributaries to the Missouri and Mississippi Rivers had been dredged and straightened. In Iowa, a state touched by one of this paper's watersheds, streams with watersheds over 129 square kilometers (31,877 acres) lost 45 percent of their length to channelization (USFWS, 1975). Locally, Lenhart et al. (2011b) reviewed the 1855 General Land Office survey map and noted many sloughs were graded or channelized, overall decreasing Elm Creek and its neighbor Center Creek by approximately 20 percent of their headwater stream length.

Channelization increases the speed with which water leaves the landscape, causing channel widening. The term channelization encompasses alterations designed to straighten (shorten) streams to remove water from the landscape faster, and/or move a channel to a new location. Simon and Rinaldi (2006) points out that when vegetation is removed during channelization, the stream's hydraulic roughness is decreased, which increases velocity, stream power, peak discharges and overall erosion rates.

In response to the newfound sediment-velocity imbalance, channelized streams downcut (incised) and widened. In responses to channelization, Midwestern loess watersheds widening by about 30 meters (98 feet) (a fivefold increase) and incising 6 meters (20 feet) (a fourfold increase); and West Tennessee widening by about 5 meters (16 feet) per year since the mid 1800s (Piest et al., 1976, 1977).

Locally, Scottler et al. (2013) found southern Minnesota channels widening by 10 to 40 percent. MPCA (2012a) and Lenhart (2008) also reviewed southern Minnesota streams for width changes. MPCA (2012a) compared the 1855 dimensions of 7 streams at 58 total locations to present day widths. The majority of reaches (46 total or 79 percent) widened, but some (12 total or 21 percent) narrowed. The streams changed from -70 percent to 1200 percent in width; on average increasing by 115 percent. Lenhart (2008) reviewed relict channel data of Elm Creek, finding a number of stream terraces dating back to 1860 indicating the headwaters had expanded the most, increasing by 250 percent.

The following figures illustrate the change of hydrologic storage capacity of the study watersheds over time. Red shades indicate the most storage loss, whereas green shades indicate the most storage capacity, or least disturbance. The figures also indicate channel modifications. Red and yellow channel lines indicate channel modifications, whereas blue channel lines indicate natural, or the least disturbance.

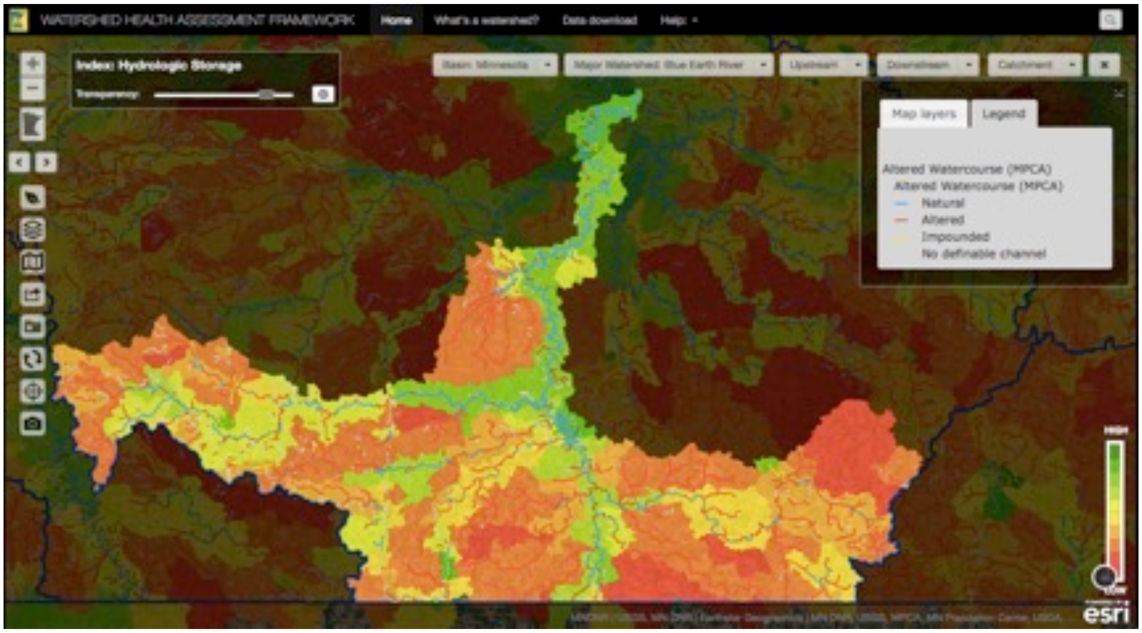

Figure 7: Elm Creek hydrologic storage and altered watercourses (WHAF, 2016)

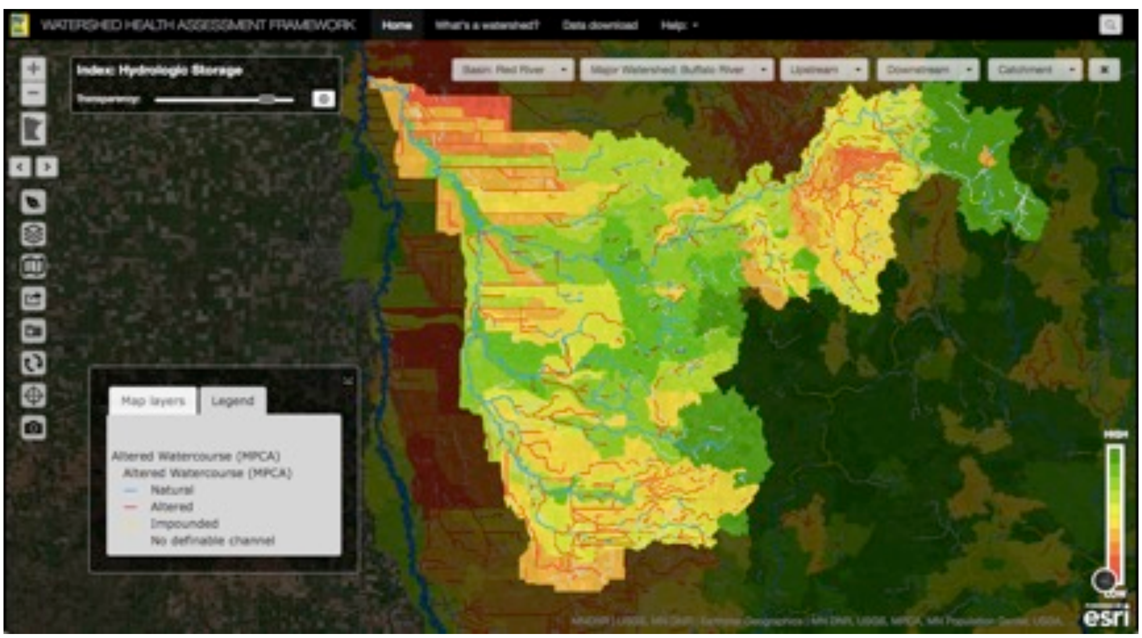

Figure 8: Buffalo River hydrologic storage and altered watercourses (WHAF, 2016)

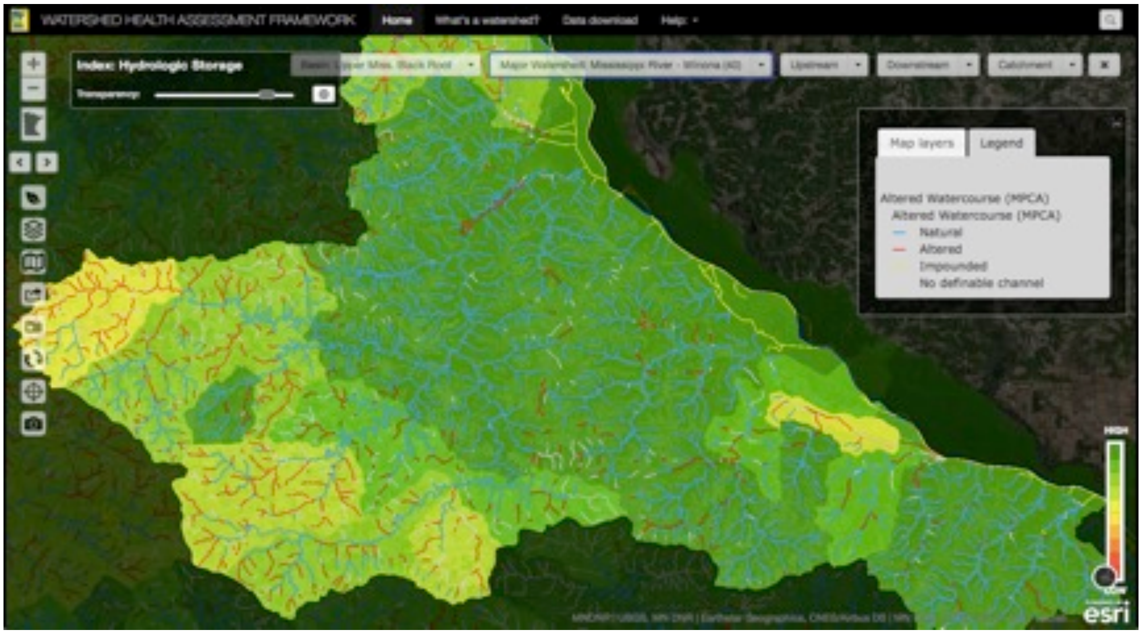

Figure 9: Whitewater River hydrologic storage and altered watercourses (WHAF, 2016)

The broad conclusion from a Greater Blue Earth River Basin study, which includes Elm Creek, was that the region's streams and rivers are unstable, experiencing and recovering from widespread hydrologic modification and land use changes as well as natural processes, and commonly impaired for high sediment loads and sediment-related phosphorus loads (MPCA, 2012b).

In particular, Lenhart et al. (2011b) surveyed Elm and Center Creek, two adjacent tributaries to the Blue Earth River. Using the channel evolution model, the study found actively maintained ditches in Stage 2 (constructed) and some artificial tributaries in Stage 3 (degradation), and 76 percent of surveyed reaches in Stage 4 (mass wasting) and Stage 5 (aggrading). Overall, the streams showed a pattern of recently disturbed headwaters (Stage 2 and 3), widening in the middle and lower reaches (Stage 4), and nearing equilibrium in the lowest reaches (Stages 5 and 6).

The Lenhart et al. (2011b) finding was nearly identical to a 1995 U.S. Army Corps of Engineers finding cited by Simon and Rinaldi (2006), finding 75 percent of the nation's stream reaches are experiencing mass failures (Stage 4).

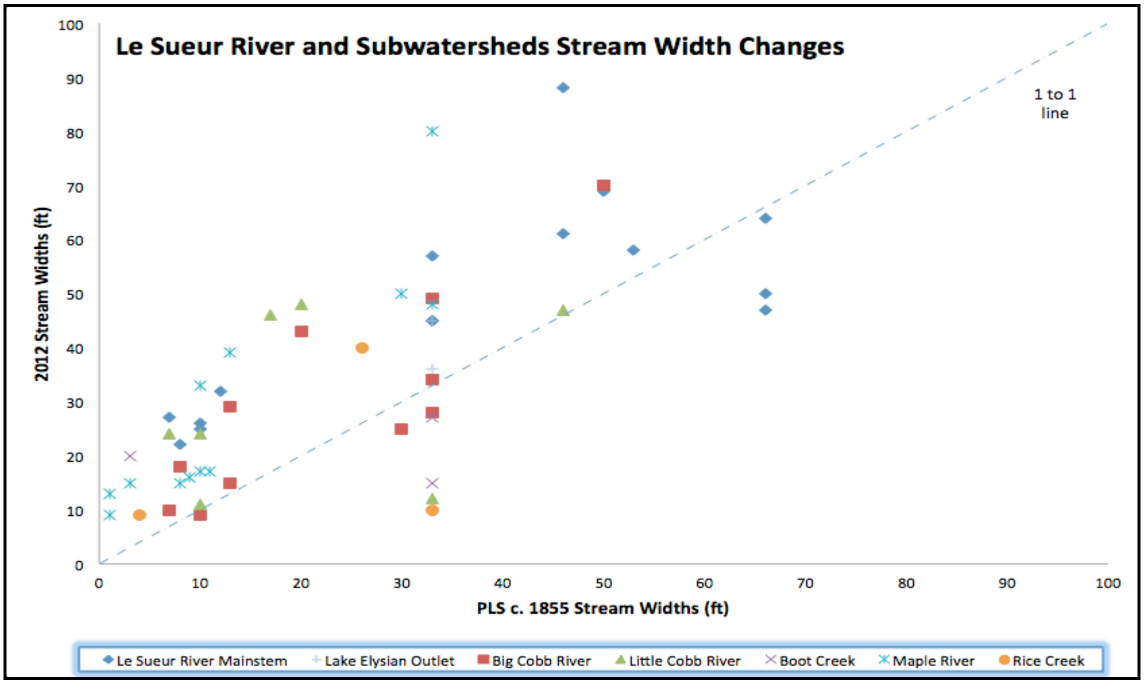

Figure 10: Stream widening in southern Minnesota watersheds (MPCA, 2012a)

1.4. Summary

Stream channels are constantly changing. They may change slowly and predictably, or rapidly in response to a disturbance. Disturbances can include channel dredging and wetland drainage for historical flood control efforts, watershed developments, and natural storm events. Channels can react to disturbances by eroding vertically, or horizontally. Channel erosion can contribute a significant percentage of a stream's sediment load. A sediment load above the tolerances of the stream's inhabitants or functions is considered an impairment. All three study streams are impaired for turbidity.

A restoration, or reduction of turbidity from channel sources, may be difficult due to the complexity of interactions between erosion rates, soils, geomorphology, chemistry, vegetation, hydrology and stream size. The next chapters cover methods of measuring erosion rates, erosion rates of the study streams, channel characteristics of the study streams, a comparison of erosion rates to channel characteristics, other restoration prioritization efforts in the watersheds, and values and policies affecting turbidity.

Chapter 2: Analyzing Lateral Erosion Measurement Tools

2.1. Introduction

Every year, hundreds of billions of kilograms (billions of tons) of sediment are carried along river systems all across the United States (Campanella, 2013). Streambank erosion can account for as much as 85 percent of suspended sediment load (Wilkin and Hebel, 1982; Hamlet et al., 1983; Odgaard, 1984; Odgaard, 1987; Simon, 1996; Bull, 1997; Trimble, 1997; Bull, 1998; Lawler et al., 1999; Simon, 1999; Walling et al., 1999; Schilling and Wolter, 2000; Simon, 2000; Sekely et al., 2002; /Amiri-Tokaldany et al., 2003; Evans et al., 2006; Wynn and Mostaghimi, 2006a; Fox et al., 2007; Wilkinson, 2009).

Bank retreats of 1.5 to 1,100 meters (5 to 3600 feet) per year across the nation (Simon, 2000) can damage property and productivity, and degrade habitat and water quality. Eroding channels can encroach upon the foundation of bridges, farmland and homes. Sediment suspended in waterways can diminish aquatic habitat by depositing on spawning grounds, blocking light from plants, make hunting difficult for aquatic predators, and make water too erosive for inhabitants. Sediment laden water can carry phosphorus pollution. A decade ago, the United States spent approximately $16 billion annually cleaning water polluted by sediment (Wynn and Mostaghimi, 2006a); a number that has likely increased with time.

With a significant portion of suspended sediment coming from bank erosion, slowing bank retreat strategically is a priority for resource managers. Managers planning to control bank erosion efficiently over the course of a stream benefit from a knowledge of the stream's lateral erosion rates. Additionally, state and federal regulatory and grant programs aimed at reducing sediment loading may require quantification of sediment sources, using reliable measurement tools. Common means of conceptualizing or measuring stream erosion rates include GIS, BEHI, BSTEM, BANCS and bank pins.

2.1.1. Objectives

The objectives of this chapter were to:

1. Measure lateral erosion rates on three agriculture-dominated Minnesota streams using four tools: the DNR Static Lateral Migration Tool, the BBE Dynamic Lateral Migration Tool, the NCED Planform Statistics Tool, and BANCS.
2. Compare the erosion rates measured by these four lateral erosion rate tools.

2.2. Materials and Methods

2.2.1. Tools and Statistics

2.2.1.1. GIS Measurements

Over the years, GIS-based aerial photography analysis has proven to be a reliable and practical means of measuring a stream's movement over large temporal and spatial scales (Rood et al., 2014; DeRose and Basher, 2011; Hooke, 1989; Micheli and Kirchner, 2002; Finlayson et al., 2004). Findley et al. (2012), Rasdorf et al. (2011), and Hermann and Klette (2007) compared field-surveyed roadways to GIS-measured aerial photography. They concurred that GIS was a practical and precise method of taking field measurements. This study uses two such GIS-based lateral erosion tools: one by Mark Ellefson from the Minnesota Department of Natural Resources (DNR Static Lateral Migration Tool in text, or Ellefson Tool in graphs); and one by Mikhail Titov from the University of Minnesota's Bioproducts and Biosystems Engineering (BBE Dynamic

Lateral Migration Tool in text, or Titov Tool in graphs).

Considering the lessons learned by other researchers, this study used high-quality aerial photography, chosen for abundant road crossings (benchmarks/waypoints), clear views of the streams, and free from weather events (such as floods). The photography was orthorectified, quality checked and mosaicked. Centerlines were drawn twice on each stream, one centerline at the beginning of the study period, and one at the end. When the river was not clearly visible (on 1 of 149 reaches), a digital elevation model (DEM) from a year similar to the subject year was used to see through the trees.

The time period between observation years was maximized, based on image quality. The goal was to use the same years for each river, comparing 1991 to 2010 on Elm Creek and the Buffalo River. Restoration work on the Whitewater River and several subsequent years of missing imagery, however, resulted in the use of later imagery over a slightly shorter period for this stream, comparing 2003 to 2010. The 1991 and 2010 centerlines for Elm Creek and the Buffalo River, as well as the 2003 and 2010 centerlines for the Whitewater River were loaded into the DNR Static Lateral Migration Tool. The 1991 and 2010 centerlines for Buffalo River were also loaded into the BBE Dynamic Lateral Migration Tool.

2.2.1.1.1. GIS Lateral Erosion Tool: DNR Static Lateral Migration by Mark Ellefson

Two researchers used the DNR Static Lateral Migration tool: Oknich applied this tool to all three study watersheds; and Ellefson applied this tool to the Whitewater River.

Ellefson's DNR Static Lateral Migration Tool creates the necessary data for the ArcGIS "Feature to Polygon" to output an erosion measurement. In GIS, the user traces the centerline of the stream on aerial photography in two chosen years. The user defines reach lengths, or distances over which the lateral erosion will be measured. As the primary goal of this research was to determine if predominance of trees or grasses influenced erosion rate, a buffer created around the center lines for the three streams was broken into reaches where vegetation cover classes changed. Furthermore, Ellefson ran this tool on the Whitewater River, breaking reaches by hydrologic characteristics. The DNR Static Lateral Migration Tool populated each of these reaches with a measure of erosion rate (distance per year). More specifically, ArcGIS "Feature to Polygon" converts shapes and lines to polygons; or in this case, the area between overlapping centerlines and reach breaks becomes a string of polygons.

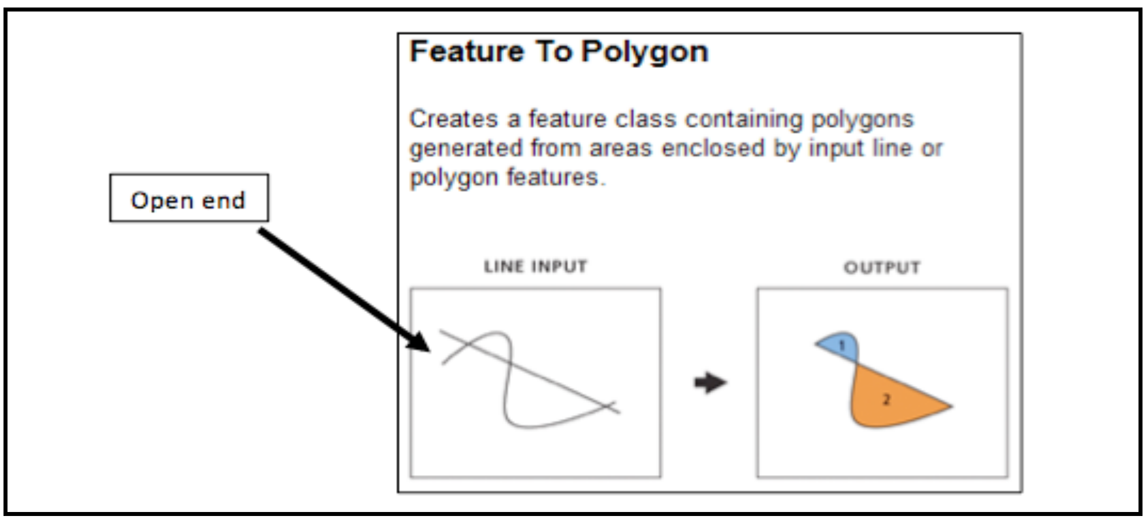

Figure 11: Feature to Polygon. Only enclosed polygons are considered (ESRI graphic adapted by Ellefson, 2016).

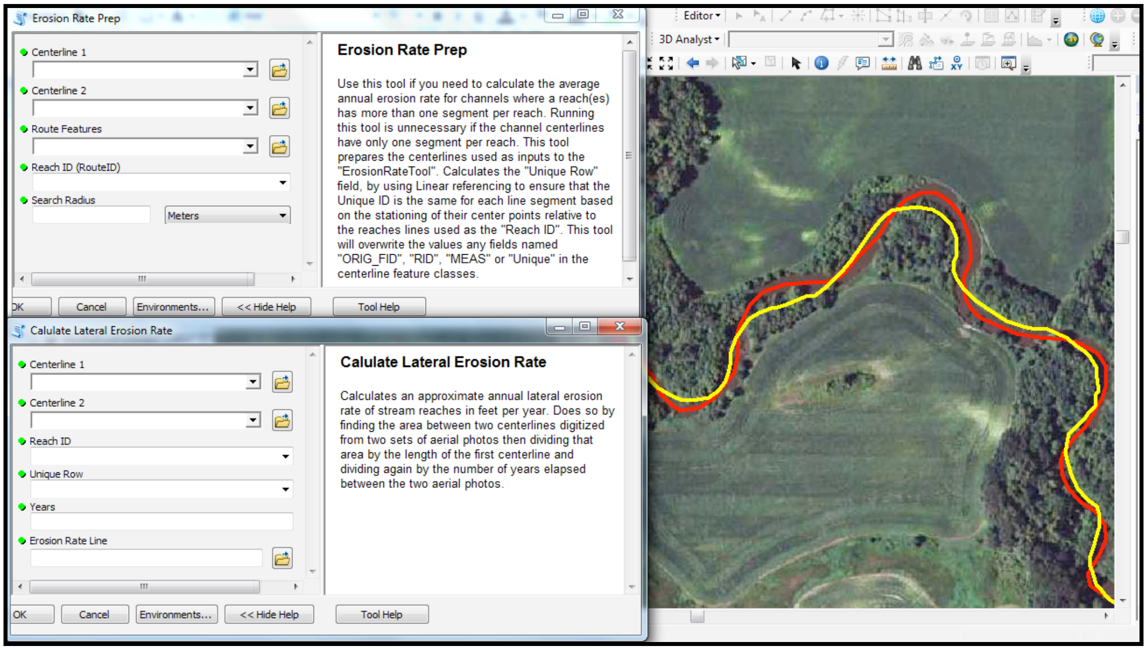

Figure 12: DNR Static Lateral Migration Tool (Ellefson, 2015)

To ensure this string of polygons is useful as a measure of eroded area (and later erosion rate), the user runs the DNR Static Lateral Migration Tool's "Erosion Rate Prep" to ensure every appropriate reach forms a closed polygon (no open ends as graphic above illustrates). This step assigns markers along the first centerline, which it matches to markers along the second centerline using linear referencing. It uses ArcGIS "Route Features" to incorporate reach breaks, which intersect the pair of centerlines. As mentioned above, reach breaks were added where vegetation cover classes changed. From most herbaceous to most trees, the cover classes were Cover 1: grass with under 20% trees, Cover 2: grass with 20 to 40% trees, Cover 3: mixed with 40 to 80% trees, and Cover 4: forested with over 80% trees. Route Features runs an error check to ensure the markers line up and polygons are closed, runs ArcGIS "XY to Line Tool," and ArcGIS "Feature to Polygon" tool. Next, the user runs the DNR Static Lateral Migration Tool's "Calculate Lateral Erosion Rate" to calculate the area of each polygon, divided by the length of the first centerline, and divided by years between centerlines to convert eroded area to lateral erosion rate (Ellefson, 2016).

The erosion rate should be viewed as an upper limit, as line segments that do not form polygons are not counted toward the total erosion. Its accuracy is limited by the accuracy of the aerial photography and its user. A strength of this tool is comparison of erosion rates between reaches. (Ellefson, 2016).

2.2.1.1.2. GIS Lateral Erosion Tool: BBE Dynamic Lateral Migration by Mikhail Titov

One researcher used the BBE Dynamic Lateral Migration tool: Titov applied this tool to the Buffalo River.

Titov (2015a) created a channel erosion tool as an alternative to the NCED Planform Statistics (Lauer, 2006) and the DNR Static Lateral Migration Tool (Ellefson, 2015). To compare the effect of reach length on erosion rates between this tool and the DNR Static Lateral Migration Tool, Titov broke the Buffalo into 10 and 300 equal segments and ran the BBE Dynamic Lateral Migration Tool. Titov and Oknich used the same set of Buffalo River centerlines to compare BBE Dynamic Lateral Migration Tool results (Titov), to DNR Static Lateral Migration Tool (Oknich).

The BBE Dynamic Lateral Migration Tool uses curvature and proximity to align two centerlines via the dynamic time warping algorithm in R (Giorgino, 2009; Titov 2015a). Dynamic time warping uses Euclidean 2-D space, which was augmented by fitting smooth splines along each centerline to create signed curvature. After this step, the user runs a QGIS Processing Framework to encompass the spline matrix, and calculate erosion rate via R project package DTW (Giorgino, 2009).

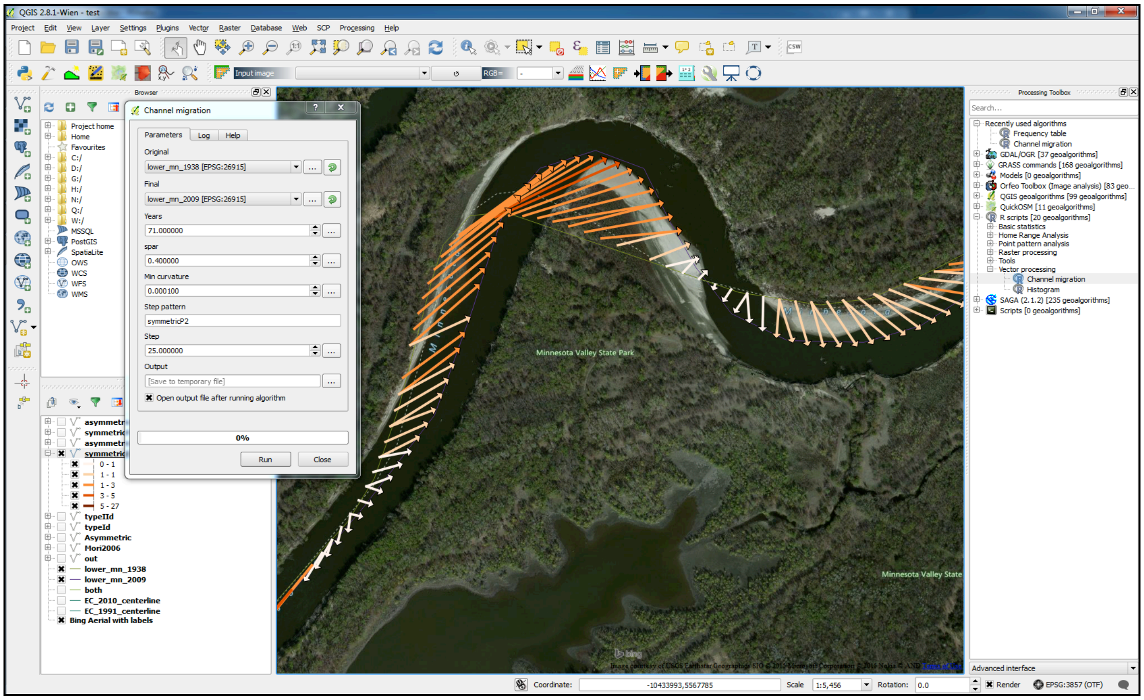

Figure 13: BBE Dynamic Lateral Migration Tool (Titov, 2015a)

2.2.1.1.3. GIS Lateral Erosion Tool: NCED Planform Statistics by Wes Lauer

Two researchers used the NCED Planform Statistics Tool: Ulrich and Oknich applied this tool to the headwaters of Elm Creek. Use of it was ultimately discontinued after the discovery of the DNR Static Lateral Migration Tool.

The NCED Planform Statistics Tool measures width, curvature and channel erosion rate at discrete points along a stream. It is comprised of three tools: Tool 1: Interpolate centerlines from two bank lines; Tool 2: Lateral distance measurement; Tool 3: Bank buffer boxes.

In order to determine lateral erosion rates using the NCED Planform Statistics Tool, both banks of two aerial photographs (four banks) were digitized before running Tool 1. Tool 1 determined the centerline of the stream in each year using these four bank lines, divide the stream into evenly-spaced polygons, and measure width and radius of curvature within each polygon. Tool 2 set Bezier curves along and normal to the older aerial photograph's centerline, terminating along the newer centerline. The lengths of these curves, which are assumed to best fit the river's movement, were recorded as lateral erosion. Lateral erosion measurements were made at increments along the stream set by Tool 1. Tool 3 projected the lateral erosion polygons onto the upland banks a set distance.

2.2.1.2. BANCS Method

BANCS, or Bank Assessment for Non-point source Consequences of Sediment, was published by Rosgen (1996), building on his Bank Erosion Hazard Index (BEHI) and near bank stress (NBS) tools. BEHI and NBS measurements include several physical characteristics of a stream's banks, such as dimensions and rooting characteristics. BANCS pairs BEHI and NBS measurements with measured erosion data to produce an erosion rate prediction which can be applied to similar systems. Several researchers from the University of Minnesota and the Department of Natural Resources applied this method to the three streams by recording field characteristics and walking the values through a series of predetermined calculations.

Analysis of the GIS lateral erosion data, and complementary near bank stress data allows for creation of an erosion prediction graph using the BANCS relationships. The Whitewater River erosion prediction graph (Figure 24) was developed by the Minnesota Department of Natural Resources using cross-section, bank pin, GIS erosion, near bank stress and BEHI data. The Elm Creek and Buffalo River erosion prediction graphs (Figures 22 and 23) were created by adjusting the Whitewater River slope to match each stream's lateral erosion and near bank stress data.

2.2.1.3. Statistics

The objective of this analysis was to compare the erosion rate measurements of three rivers, using three erosion tools, and several researchers. This will not be reviewing the drivers of erosion, or evaluating why one tool applied to three different streams obtains three different erosion rates. This will review how the erosion rates obtained from the DNR Static Lateral Migration Tool, BBE Dynamic Lateral Migration Tool and BANCS method compare. This simple comparison used basic statistics (minimum, maximum, median, mean, geomean, variance, standard deviation); and boxplots (maximum, third quartile, mean, first quartile, minimum) by method (DNR Static Lateral Migration Tool, BBE Dynamic Lateral Migration Tool, BANCS), by stream (Elm, Buffalo, Whitewater), and all together. To determine if the values were statistically different, Kruskal-Wallis was applied.

Kruskal-Wallis a nonparametric test, used when data are not normally distributed, different groups collect the data, and there are three or more variables. The Kruskal-Wallis test groups and ranks data before separating the ranks and computing H to approximate rank variance (Bluman, 2011). If the H value is large enough, the null hypothesis – which is that the means are from the same group – is rejected. In this case, the erosion rates from the different groups would be different.

Formula for the Kruskal-Wallis Test

$$H = \frac{12}{N(N+1)}\left(\frac{R_1^2}{n_1} + \frac{R_2^2}{n_2} + \cdots + \frac{R_k^2}{n_k}\right) - 3(N+1)$$

where

R_1 = sum of ranks of sample 1
n_1 = size of sample 1
R_2 = sum of ranks of sample 2
n_2 = size of sample 2
.
.
.
R_k = sum of ranks of sample k
n_k = size of sample k
$N = n_1 + n_2 + \cdots + n_k$
k = number of samples

Figure 14: Kruskal-Wallis test (Bluman, 2011)

2.2.2. Study Area

All three streams examined in this study require an investment to remove excessive sediment, which prevents them from fulfilling uses designated through the Clean Water Act. Each drains an agriculture-dominated watershed, in different ecoregions of the state. Elm Creek in south-central Minnesota, the Buffalo River in western Minnesota, and the Whitewater River in southeastern Minnesota are impaired by their sediment loads.

2.2.2.1. Elm Creek

Elm Creek delivers water from 700 square kilometers (173,000 acres) of Martin and Jackson counties in south central Minnesota into the Blue Earth River, which drains into the Minnesota River then the Mississippi River. Elm Creek's watershed is dominated by row crop agriculture, with 86 percent of land producing corn and soybeans (Quade, 2000; Lenhart et al., 2010; MPCA, 2012b). Lenhart (2008) reviewed historic data to determine the stream had enlarged by as much as 250 percent in the headwaters, and had left behind several terraces as it adjusted to land use changes.

Prior to row crop agriculture, Elm Creek drained a prairie pothole watershed, with nearly 50 percent wetland coverage (Quade, 2000). European settlers began converting prairie and draining wetland to make way for farmland. In the early 1900s, public ditch systems were created to drain wetlands (MPCA, 2012b). In the past fifty years, planting of row crops has expanded significantly, and in the past thirty years, ditching and tiling efforts have intensified. Currently the Greater Blue Earth River Basin contains 5,446 kilometers (3,384 miles) of public drainage (ditch and tile) (MPCA, 2012b), and an unknown, but doubtlessly large mileage of private drainage, leaving wetland cover at under 2 percent (Quade, 2000) of Elm Creek's watershed. Coincidentally, precipitation has also increased across Minnesota in the past thirty years. Channel adjustments the creek made to prairie conversion were repeated as the intensity of land use and runoff volume increased.

As the stream adjusted, it incised a 0.002 to 0.0003 m/m channel through alluvial silt and clay loams of Des Moines Lobe till (Quade, 2000; Lenhart, 2008). Lenhart (2008) found the streambeds consist of silt to fine gravel. Quade (2000) estimates Elm Creek is eroding 272,155 to 362,874 kilograms per square kilometer (1.2 to 1.6 tons per acre) per year. The fine-texture of the channel and bed material allows the water to suspend upwards of 193 mg/L of sediment (Lenhart et al., 2011b). This value, and others like it, ranks Elm Creek as one of the highest contributors of sediment to the Blue Earth River, which is the largest contributor of sediment to the Minnesota River (Quade, 2000; Lenhart et al., 2011b), a river known for its muddy appearance. Elm Creek is currently listed as impaired for fish bioassessments, turbidity (four reaches), *Escherichia coli*, and dissolved oxygen (MPCA, 2015a).

2.2.2.2. Buffalo River

The Buffalo River drains 3,100 square kilometers (768,000 acres) of Clay, Becker, Otter Tail and Wilkin counties of west central Minnesota into the Red River of the North, which continues through Canada's Lake Winnipeg and Nelson River on its way to Hudson Bay. The Buffalo River watershed is also predominantly agriculture, with 78 percent in production, 7 percent forested, 5 percent urban, 4 percent grassland, and 3 percent each open water and wetland (MPCA, 2014). Originally, the Buffalo River Watershed was a mix of forest, lake and prairie. Soils understandably range from gravel to silt and clay as the river moves from glacial moraines, and over ancient beach ridge on its way to the bed of Glacial Lake Agassiz (MPCA, 2012c).

Similar to other streams, the Buffalo River channel changed as settlers developed its watershed, and again as land use intensified (MPCA, 2014). At present, the Buffalo River has adjusted to increased flow and sediment loading by growing generally more erosive, digging deeper, widening, and losing touch with its floodplain. The MPCA (2014) shows a list of negative aquatic habitat and water quality responses, such as habitat loss from lack of pool scour, accumulation of fine sediment in pools and hyporheic zone (region beneath and alongside a stream bed where mixing of ground and surface water occurs), loss of hyporheic zone productivity, loss of in-stream and overhead vegetation, degradation of substrate composition, increased temperature, decreased dissolved oxygen, degraded macroinvertebrate community, loss of spawning and rearing habitat, loss of habitat diversity and integrity, increased sediment supply, and accelerated bank erosion. Altered hydrology has been identified as the factor most stressing stream biology within the Buffalo River (MPCA, 2014). The Buffalo is currently listed as impaired for *Escherichia coli* (eight reaches), aquatic macroinvertebrate bioassessment (two reaches), fish bioassessment, turbidity (eight reaches), and dissolved oxygen (MPCA, 2015a).

2.2.2.3. Whitewater River

The Whitewater River drains 830 square kilometers (205,000 acres) of Olmstead, Winona and Wabasha counties on its way to the Mississippi River in southeastern Minnesota. The watershed is 66 percent agriculture (58 percent crops, 8 percent pasture), 14 percent wetland and wildlife management area, 13 percent woodland, and 7 percent other (MPCA, 2010). The headwater streams flow through gently rolling hills before cascading down limestone bluffs and ravines to a slough along the Mississippi. Originally this area's highly erodible loess soils were covered in prairies, oak savannah and hardwood forest (WRWP, 2016).

The Whitewater River channel has evolved with land use changes. Lands were cleared for wheat farming in the 1850s (in 1868 the area became the nation's fourth largest wheat market), which switched to dairy and its supporting grasses and grains near 1900s (WRWP, 2016). Dairy remained dominant until relatively recently, when intensive row-crop agriculture took over (MPCA, 2010). Of the three subject watersheds, the Whitewater has the most perennial cover (wetland, WMA, woodland and pasture comprise 35 percent), but also the most relief change.

The river has also been especially prone to flooding. It is widely known that the watershed has turned upside-down in the past several generations: Much of the soil from the headwaters has moved through the valleys and gullies to fill the lower reaches. In the 1920s and 1930s, the river was flooding 20 or more times per year (WRWP, 2016). As far back as the 1920s, once-productive farms were buried under 4.6 meters (15 feet) of soil (WRWP, 2016). After nearly 100 more years of flooding, there is more soil on pre-settlement lands. The Whitewater River is currently listed as impaired for turbidity (9 reaches) and nitrates (2 reaches) (MPCA, 2015a).

2.3. Results and Discussion

As mentioned above, the objectives of this chapter were to measure lateral erosion rates with several tools, and compare those results. This section first views streams using the same tool to get an overview of how the streams look, then compares the tools within each stream, then compares all the data together, and finally covers the erosion rate prediction graphs.

2.4.1. Comparing the Streams by Tool

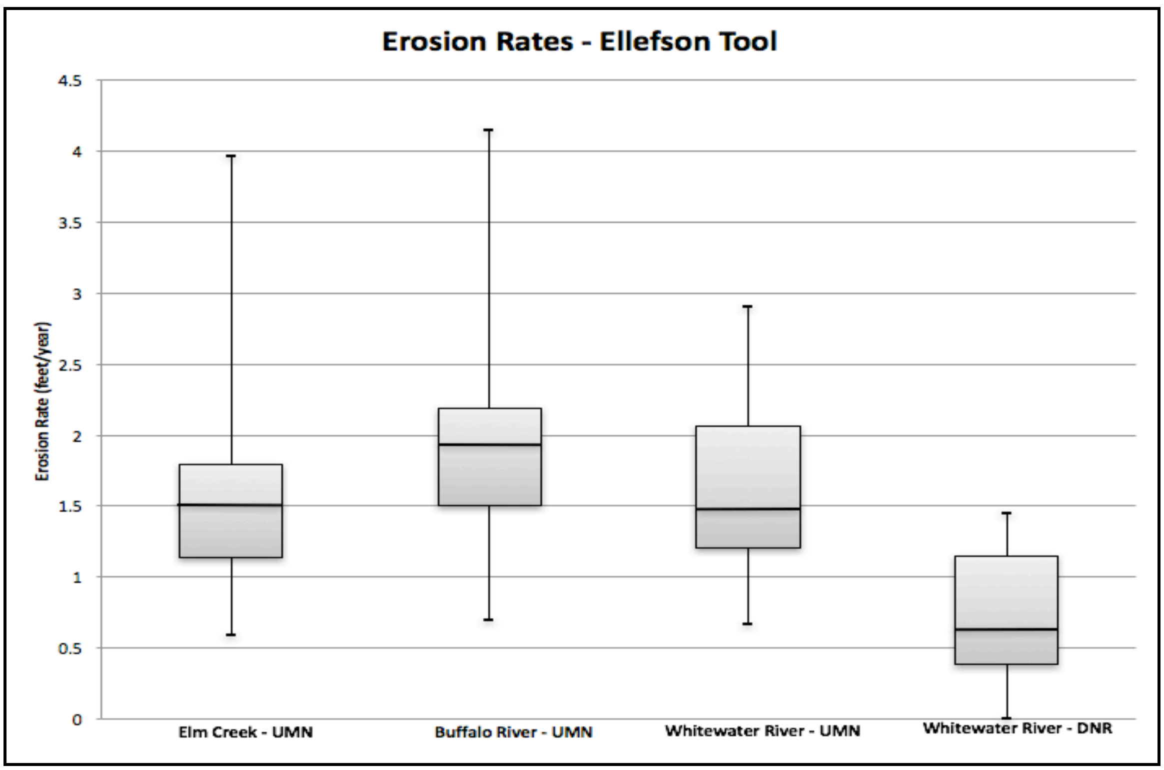

Figure 15: DNR Static Lateral Migration Tool erosion rates (in feet): Elm Creek, Buffalo River and Whitewater River (Oknich). From top to bottom, these boxplot markers are the maximum, third quartile, mean, first quartile and minimum values.

Comparison of 1991 and 2010 aerial photography showed average Elm Creek erosion rates at 0.48 meters (1.57 feet) per year. The rates ranged from 0.2 to 1.2 meters (0.6 to 4.0 feet) per year, with a median of 0.5 (1.5), variance of 0.03 (0.1) and standard deviation of 0.2 (0.6) feet per year. The first quartile was 0.3 (1.1) and the third quartile was 0.6 meters (1.8 feet) per year.

Comparison of 1991 to 2010 aerial photography showed average Buffalo River erosion rates at 0.6 meters (1.9 feet) per year. The rates ranged from 0.2 to 1.3 meters (0.7 to 4.2 feet) per year, with a median of 0.6 (1.9), variance of 0.03 (0.1) and standard deviation of 0.2 (0.6) feet per year. The first quartile was 0.5 (1.5) and the third quartile was 0.7 meters (2.2 feet) per year.

Comparison of 2003 to 2010 aerial photography showed average Whitewater River erosion rates at 0.5 meters (1.63 feet) per year. The rates ranged from 0.2 to 0.9 meters (0.7 to 2.9 feet) per year, with a median of 0.5 (1.5), variance of 0.1 (0.4) and standard deviation of 0.2 (0.7) feet per year. The first quartile was 0.4 (1.2) and the third quartile was 0.6 meters (2.1 feet) per year.

Comparison of 1991 to 2011 aerial photography by DNR showed average Whitewater River erosion rates at 0.2 meters (0.7 feet) per year. The rates ranged from 0 to 0.5 meters (0 to 1.5 feet) per year, with a median of 0.2 (0.6), variance of 0.1 (0.3) and standard deviation of 0.2 meters (0.6 feet) per year. The first quartile was 0.1 (0.4) and the third quartile was 0.3 meters (1.1 feet) per year.

Of the three rivers, Elm Creek had many of the lowest erosion rates across its 119 reaches, with the Buffalo River having most of the highest erosion rates across its 109 reaches. While these agriculture-dominated watersheds are alike in many ways, they also have many differences. However, a comparison of watersheds, and their dominant erosion variables is not the purpose of this chapter. Comparing these data to other datasets, however, is the purpose of this chapter.

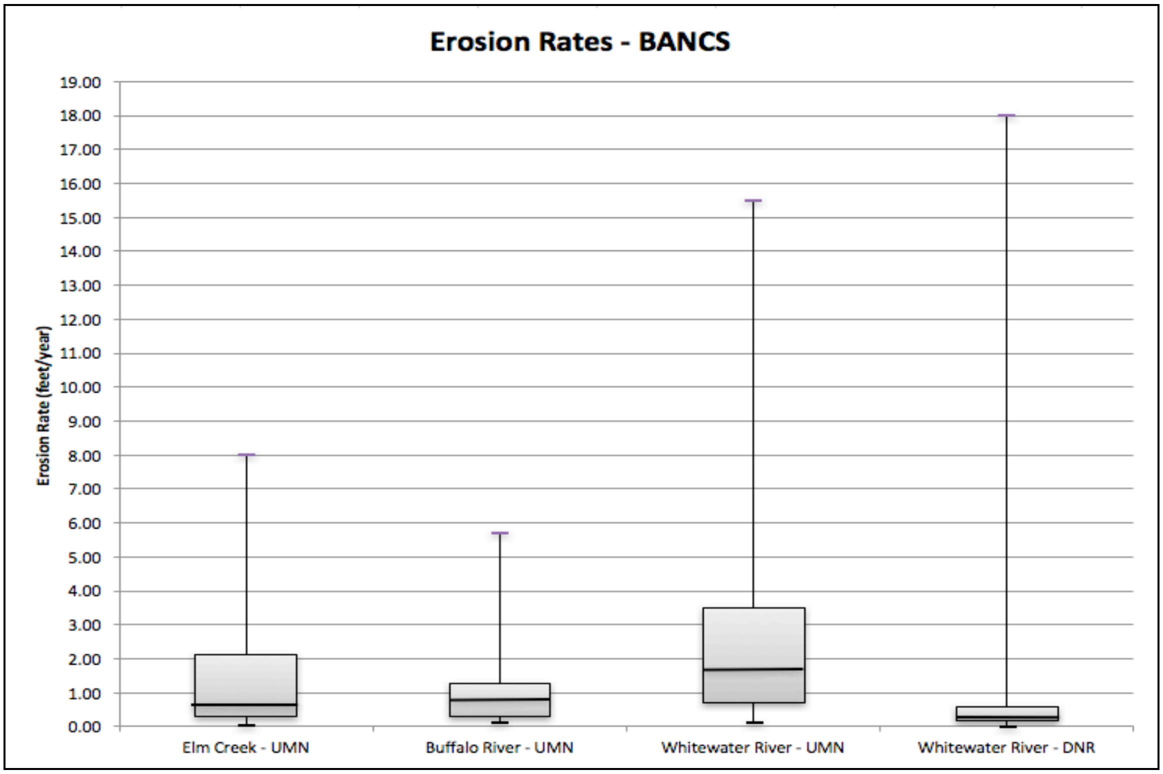

Figure 16: BANCS erosion rates (in feet): Elm Creek (UMN), Buffalo River (UMN) and Whitewater River (UMN and DNR). From top to bottom, these boxplot markers are the maximum, third quartile, mean, first quartile and minimum values.

Elm Creek BANCS data showed average erosion rates at 0.5 meters (1.7 feet) per year. The rates ranged from 0.01 to 2.4 meters (0.04 to 8.0 feet) per year, with a median of 0.2 (0.7), variance of 1.6 (5.2) and standard deviation of 0.7 meters (2.3 feet) per year. The first quartile was 0.1 (0.3) and the third quartile was 0.6 meters (2.1 feet) per year.

Buffalo River BANCS data showed average erosion rates at 0.3 meters (1.1 feet) per year. The rates ranged from 0.03 to 1.7 meters (0.1 to 5.7 feet) per year, with a median of 0.2 (0.7), variance of 0.5 (1.8) and standard deviation of 0.4 meters (1.3 feet) per year. The first quartile was 0.1 (0.3) and the third quartile was 0.4 meters (1.3 feet) per year.

Whitewater River BANCS data from UMN researchers showed average erosion rates at 0.9 meters (2.9 feet) per year. The rates ranged from 0.03 to 4.7 meters (0.1 to 15.5 feet) per year, with a median of 0.5 (1.8), variance of 3.3 (11) and standard deviation of 1 meter (3.3 feet) per year. The first quartile was 0.1 (0.4) and the third quartile was 0.3 meters (1.1 feet) per year. The Whitewater River (UMN) had the highest BANCS erosion rates in terms of mean, geomean, median and minimum. It also has the highest variance and standard deviation.

Whitewater River BANCS data from DNR researchers showed average erosion rates at 0.3 meters (1.0 feet) per year. The rates ranged from 0 to 5.5 meters (0.01 to 18.0 feet) per year, with a median of 0.1 (0.3), variance of 2.3 (7.4) and standard deviation of 0.8 meter (2.7 feet) per year. The first quartile was 0.1 (0.2) and the third quartile was 0.2 meters (0.6 feet) per year. The Whitewater River (DNR) had the highest maximum BANCS erosion rates.

2.4.2. Comparing the Tools by Stream

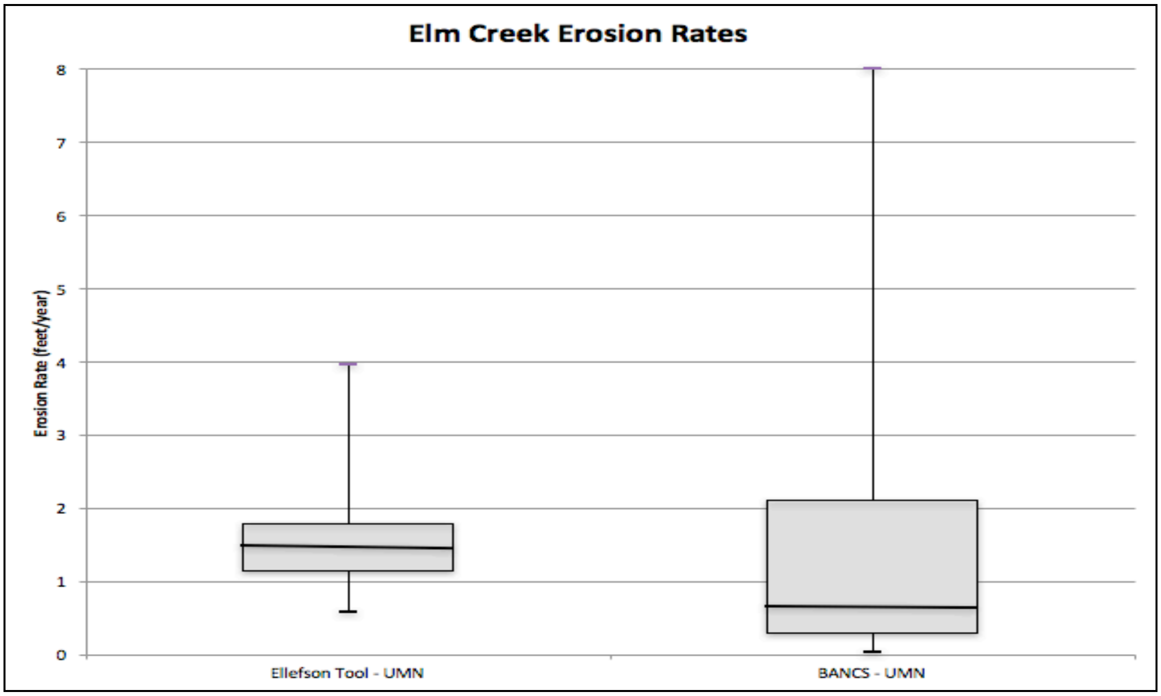

Figure 17: Elm Creek erosion rates (in feet) using DNR Static Lateral Migration Tool (Oknich) and BANCS (UMN). From top to bottom, these boxplot markers are the maximum, third quartile, mean, first quartile and minimum values.

The values represented in Figure 17 were covered above. Generally, the erosion rate values for Elm Creek were higher from the DNR Static Lateral Migration Tool than from the BANCS method. The range of values for the BANCS method were much wider, with the maximum erosion rate twice as high as the DNR Static Lateral Migration Tool results.

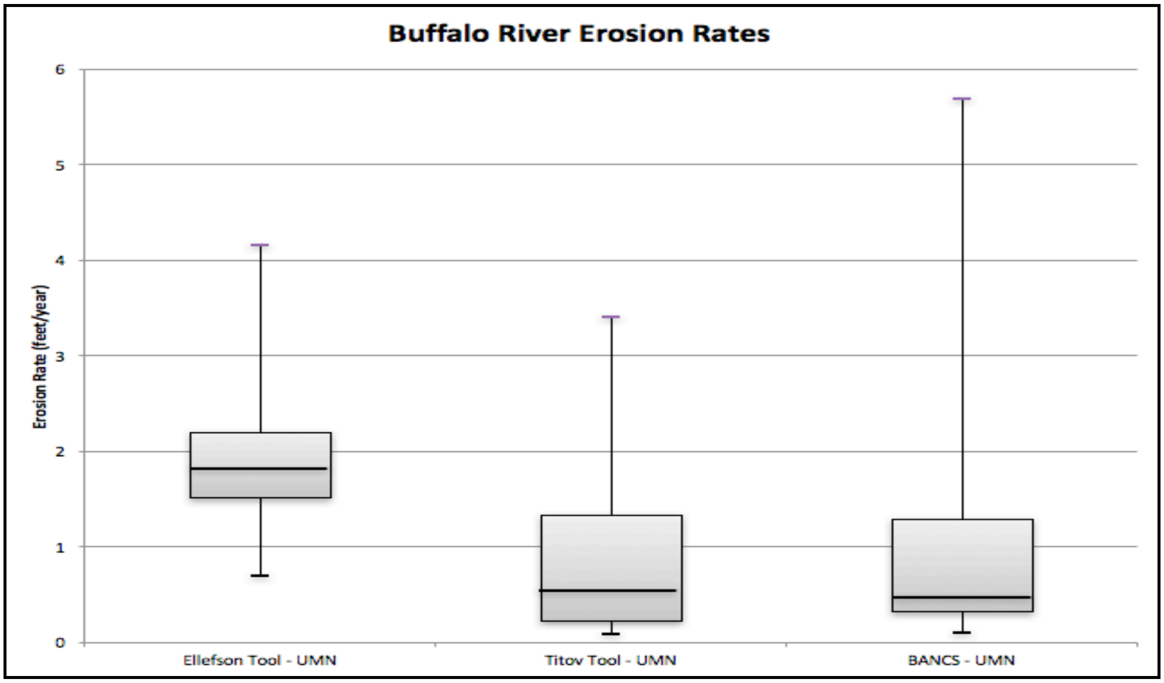

Figure 18: Buffalo River erosion rates (in feet) using DNR Static Lateral Migration Tool (Oknich), BBE Dynamic Lateral Migration Tool (Titov) and BANCS (UMN). From top to bottom, these boxplot markers are the maximum, third quartile, mean, first quartile and minimum values.

The Buffalo River DNR Static Lateral Migration Tool and BANCS numbers were covered above. The average BBE Dynamic Lateral Migration Tool erosion data was 0.3 meters (0.9 feet) per year. The rates ranged from 0.03 to 1.0 meters (0.1 to 3.4 feet) per year, with a median of 0.2 (0.6), variance of 0.2 (0.7) and standard deviation of 0.2 meters (0.8 feet) per year. The first quartile was 0.1 (0.2) and the third quartile was 0.4 meters (1.3 feet) per year.

Erosion rates were highest with the DNR Static Lateral Migration Tool considering minimum, median and first and third quartile. BBE Dynamic Lateral Migration Tool and BANCS had similar minimum, median values and first and third quartile erosion rates. The highest maximum erosion rate was from BANCS, and lowest maximum erosion rate was from the BBE Dynamic Lateral Migration Tool.

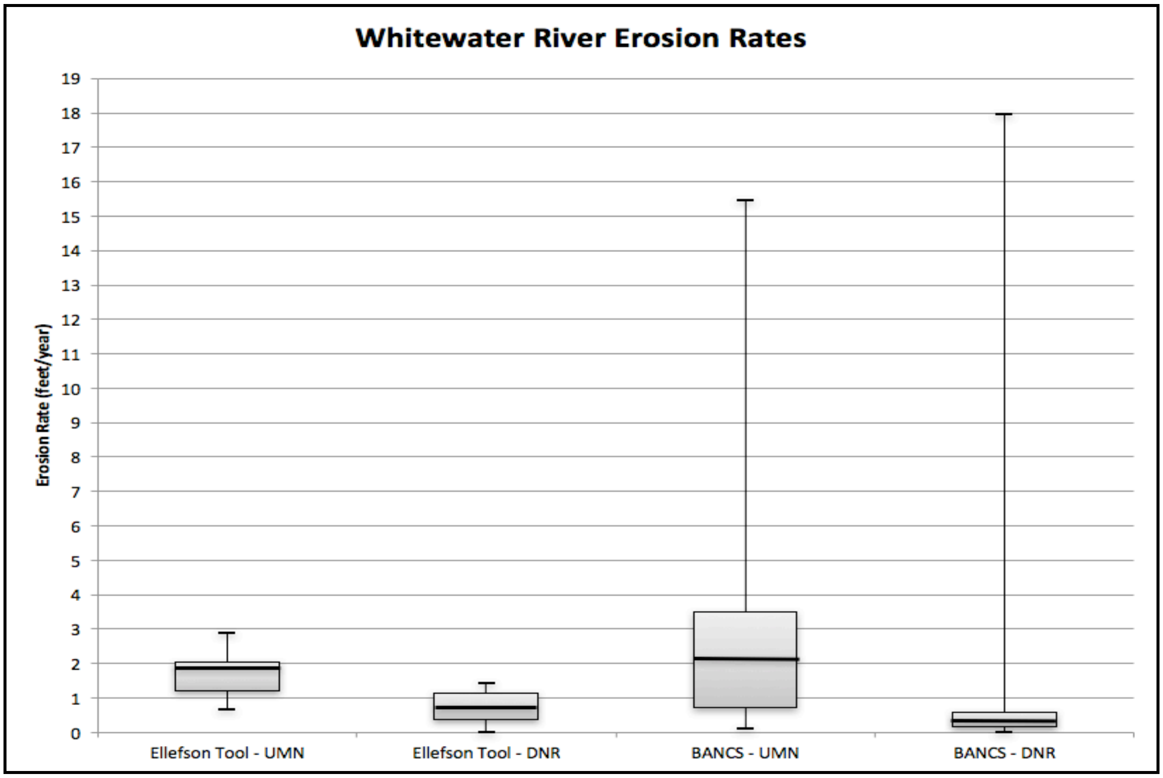

Figure 19: Whitewater River erosion rates (in feet) using the DNR Static Lateral Migration Tool (Oknich), DNR Static Lateral Migration Tool (Ellefson), BANCS (UMN) and BANCS (Ellefson); only reaches overlapping Oknich's and Ellefson's studies were compared. From top to bottom, these boxplot markers are the maximum, third quartile, mean, first quartile and minimum values.

The Whitewater River DNR Static Lateral Migration Tool (UMN and DNR), BANCS (UMN and DNR) data were covered above. The Whitewater River had the most datasets to compare, with GIS and BANCS results from UMN and DNR research. Whitewater River median erosion rates were 0.5 meters (1.5 feet) per year using the DNR Static Lateral Migration Tool (UMN), 0.2 meters (0.7 feet) per year using the DNR Static Lateral Migration Tool (DNR), 0.5 meters (1.8 feet) per year using BANCS (UMN staff) and 0.3 meters (1.0 feet) per year using BANCS (DNR staff). The UMN BANCS and DNR BANCS team found several maximum erosion rates quite high compared to GIS tools. This included a maximum erosion rate over three times higher than GIS tools.

Aside from the BANCS maximum rate, DNR found similar, but slightly smaller erosion rates than the UMN using the same tools.

2.4.3. All The Lateral Erosion Data

As mentioned above, of the GIS tools, the DNR Static Lateral Migration Tool was used the most: on all three streams, and by two users on the Whitewater. The BBE Dynamic Lateral Migration Tool was developed later in the study, and used on one stream by one user. The NCED Planform Statistics Tool was used on the headwaters of one stream by two users, but ultimately discontinued. BANCS, like the DNR Static Lateral Migration Tool, was applied on three streams, and by two users on the Whitewater.

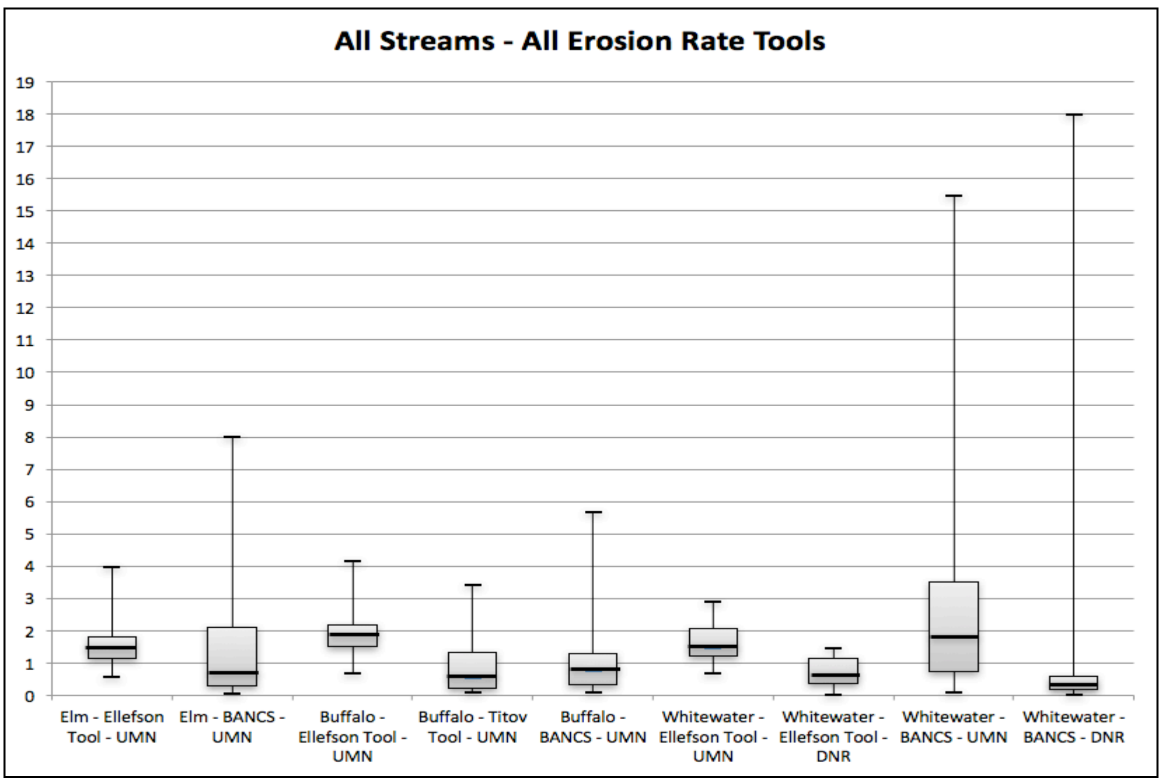

Figure 20: All erosion rates (in feet): Elm Creek using the DNR Static Lateral Migration Tool (Oknich), BANCS (UMN); Buffalo River using the DNR Static Lateral Migration Tool (Oknich), BBE Dynamic Lateral Migration Tool (Titov), BANCS (UMN); and Whitewater River using the DNR Static Lateral Migration Tool (Oknich), DNR Static Lateral Migration Tool (Ellefson), BANCS (UMN), BANCS (Ellefson). From top to

bottom, these boxplot markers are the maximum, third quartile, mean, first quartile and minimum values.

Table 1: Boxplot values, all streams, all methods (in feet)

	Elm - Ellefson Tool - UMN	Elm - BANCS - UMN	Buffalo - Ellefson Tool - UMN	Buffalo - Titov Tool - UMN	Buffalo - BANCS - UMN	Whitewater - Ellefson Tool - UMN	Whitewater - Ellefson Tool - DNR	Whitewater - BANCS - UMN	Whitewater - BANCS - DNR
Quartile 1	1.14	0.30	1.51	0.22	0.32	1.21	0.38	0.72	0.17
Minimum	0.59	0.04	0.69	0.08	0.10	0.66	0.00	0.10	0.01
Median	1.50	0.69	1.86	0.55	0.74	1.47	0.61	1.79	0.32
Maximum	3.97	8.00	4.14	3.40	5.68	2.90	1.45	15.47	17.97
Quartile 3	1.80	2.10	2.19	1.33	1.28	2.06	1.14	3.49	0.58

Figure 20 and Table 1 contain the GIS and BANCS erosion rates of all three streams, as calculated by a variety of users. The average of each dataset indicates all three streams erode between 0 and 1 meters (0 and 3 feet) per year. A Kruskal-Wallis analysis shows an adjusted H value of 311, and p value of 1.7 E-62. With more than 5 variables in this comparison, the adjusted H is treated as chi-square. The likelihood of obtaining an H value of 311 by chance is 1.7 E-62, which is unlikely, showing there is a difference between the 8 groups.

Without more analysis, it is difficult to determine which tool is more accurate: the DNR Static Lateral Migration Tool (Ellefson, 2015), BBE Dynamic Lateral Migration Tool (Titov, 2015a) or BANCS. The difference between GIS and BANCS erosion rates may be explained by several factors. GIS rates are averages across reaches of various distances, whereas BANCS rates are discrete samples. GIS tools may potentially capture some deposition, as they measure the changes of the stream over time, rather than only the erosion component. BANCS is designed to only measure erosion and its components. The GIS tools measured the movement of the three study streams, whereas the BANCS measured a number of aspects of the study streams, but used an erosion prediction graph based on western U.S. streams. Additionally, the numbers likely varied because they were calculated by a number of users.

Titov (2015b) compared Buffalo River erosion rates from the BBE Dynamic Lateral Migration Tool to those from the DNR Static Lateral Migration Tool (Figure 21). There is no direct correlation between the rates obtained by the BBE Dynamic Lateral Migration Tool and DNR Static Lateral Migration Tool erosion tools. While the results are from the same centerlines, they are from different reach breaks. To determine which GIS tool is more accurate, the results must be compared to an accurate in-field erosion measurement.

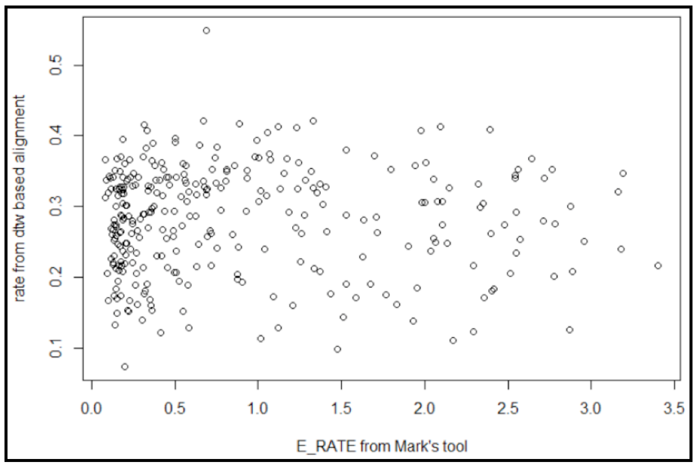

Figure 21: Comparing GIS results. BBE Dynamic Lateral Migration Tool versus DNR Static Lateral Migration Tool (Titov, 2015b) (in feet)

The average DNR Static Lateral Migration Tool erosion rates of Elm Creek and the Buffalo River were within 0.2 meters (0.8 feet) per year of their BANCS counterparts. The highest maximum rates (2.4, 1.7, 4.7, 5.5 meters per year; or 8.0, 5.7, 15.5, 18.0 feet per year) come from the BANCS calculations. BANCS maximum erosion rates were higher than aerial photography erosion rates for all three streams. As mentioned above, to better align the BANCS results with observed Minnesota erosion rates, the GIS erosion rates were used to create new erosion prediction graphs.

2.4.4. Comparing Prediction Graphs

Table 2: Elm Creek erosion percentiles (UMN, 2015)

Erosion rate descriptor	Percentile of erosion rate	Erosion rate in meters/year from aerial photos	Erosion rate in feet/year from aerial photos	Notes on site-specific information
very low	20%	0.10	0.33	Elm Creek is in the Des Moines Lobe glacial till plain, with moderately cohesive soils
low	40%	0.12	0.41	
moderate	60%	0.15	0.49	
high	80%	0.17	0.57	
very high	90%	0.21	0.70	
extreme	100%	0.37	1.21	

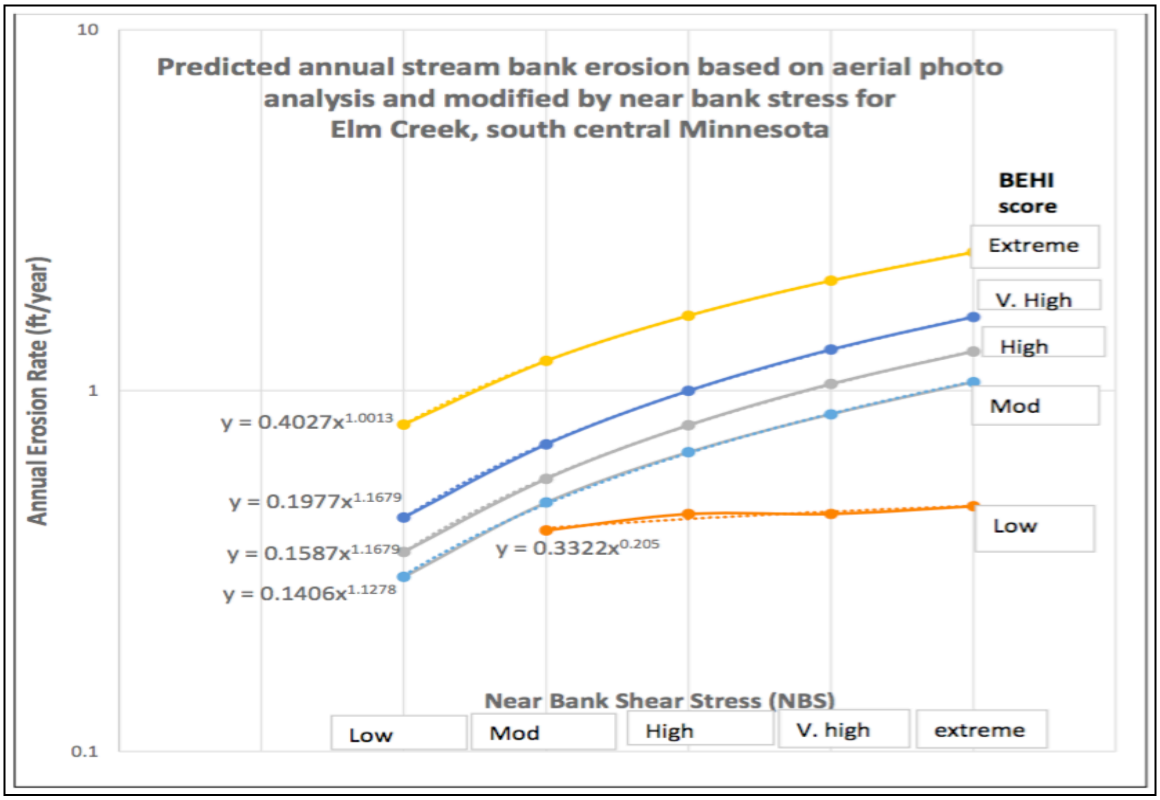

Figure 22: Elm Creek erosion prediction (MDA, 2015)

Table 3: Buffalo River erosion percentiles (UMN, 2015)

Erosion rate descriptor	Percentile of erosion rate	Erosion rate in meters/year from aerial photos	Erosion rate in feet/year from aerial photos	Notes on site-specific information
very low	20%	0.14	0.45	The Buffalo River is in the Lake Agassiz plain (Red River basin) and has cohesive soils in the lower river with coarser loams in the middle to upper reaches
low	40%	0.16	0.51	
moderate	60%	0.19	0.61	
high	80%	0.21	0.69	
very high	90%	0.23	0.76	
extreme	100%	0.38	1.26	

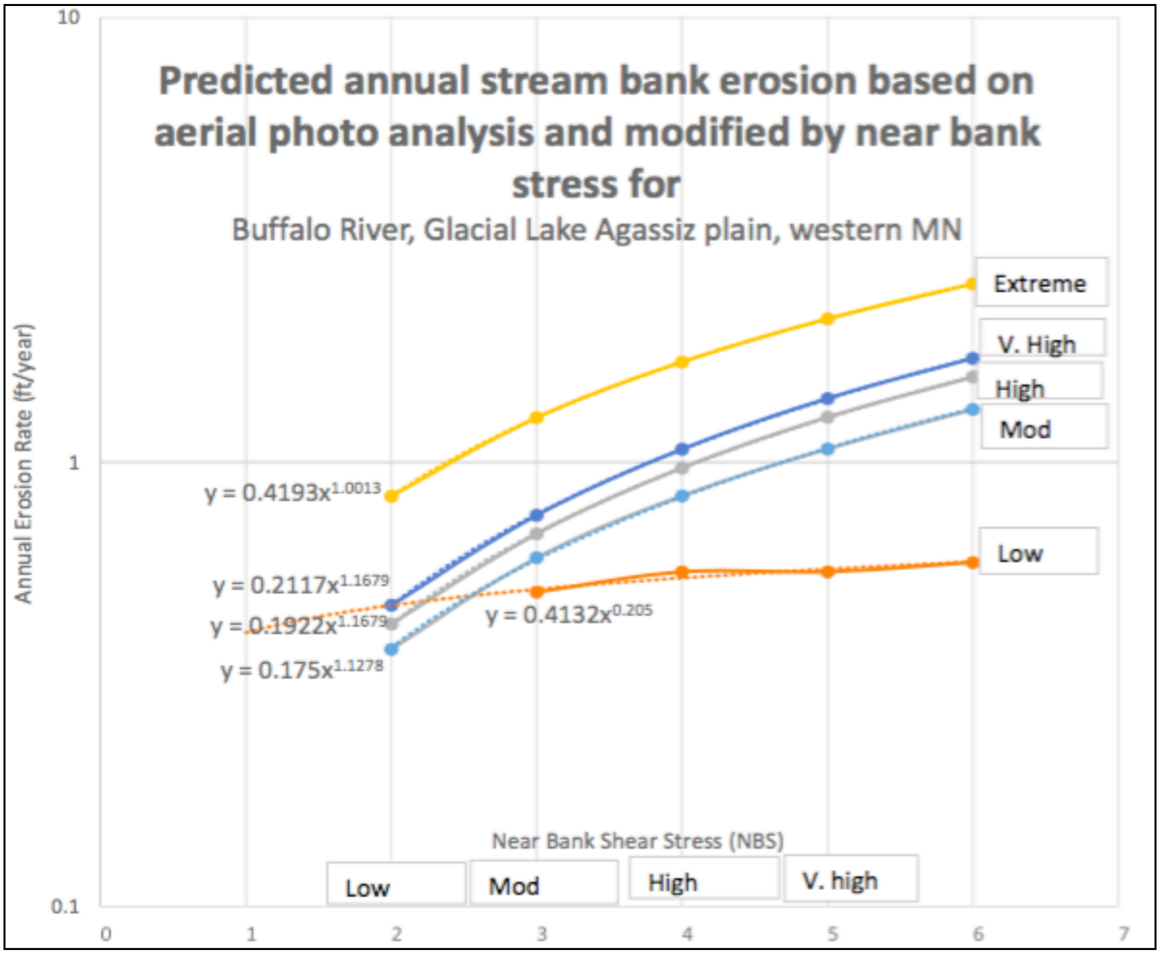

Figure 23: Buffalo River erosion prediction (MDA, 2015)

Table 4: Whitewater River erosion percentiles (UMN, 2015)

Erosion rate descriptor	Percentile of erosion rate	Erosion rate in meters/year from aerial photos	Erosion rate in feet/year from aerial photos	Notes on site-specific information
Very low	20%	0.33	1.08	The Whitewater River is in the Driftless Area and has loamy somewhat cohesive soils in the upper watershed and non-cohesive alluvial soils in the lower river.
Low	40%	0.43	1.40	
Moderate	60%	0.56	1.83	
High	80%	0.66	2.15	
Very high	90%	0.68	2.22	
Extreme	100%	0.88	2.90	

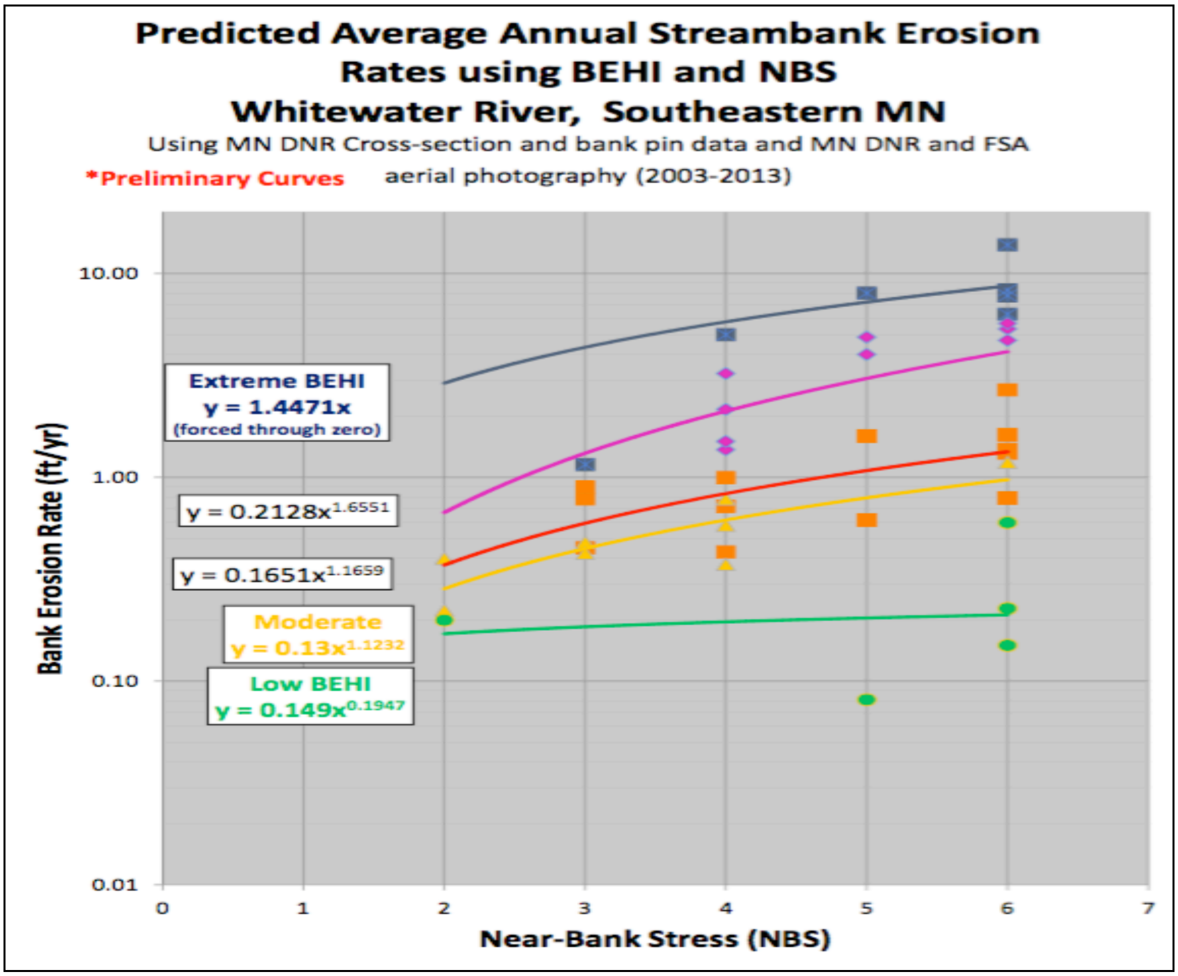

Figure 24: Whitewater River erosion prediction (MDA, 2015)

The prediction graphs are expected to make future BANCS calculations more accurately reflect locally observed erosion rates. BANCS erosion estimates have been important to resource managers developing TMDL and other stream restoration and water quality plans. All three erosion prediction graphs can be further refined by incorporating more measured erosion rates, and by developing slopes for Elm Creek and Buffalo River prediction graphs.

2.4. Conclusion

This chapter measured lateral erosion rates on three agriculture-dominated Minnesota streams using four tools: the DNR Static Lateral Migration Tool, the BBE Dynamic Lateral Migration Tool, the NCED Planform Statistics Tool, and BANCS. It then compared these erosion rates, from across three streams and several users.

As mentioned above, the three erosion estimation tools provided similar average erosion results. Generally, BANCS and UMN results were higher than GIS tools and DNR results. The GIS results may be lower because they take the movement of the entire stream into account, rather than focusing on only erosion. They may also trend lower because they average the rates over reach lengths. BANCS samples discrete sites and applies what could be unrepresentative erosion rates to the entire stream.

The tools have different resource investments, and different supporting data. BANCS erosion rates require field measurements, and therefore only capture the bank movements observed by the user; the number of sites and time span assessed is therefore more limited. However, being in the field allows the user to capture a great deal of information, such as rooting depth, rooting density, bank angles, precise plant species, and other data. BANCS erosion rates in this study have been generally higher than GIS erosion rates. The modified erosion prediction graphs for each stream, based on Minnesota erosion rates, will provide a more accurate, and regional means of estimating erosion rates.

While BANCS is a popular tool for resource managers, and the modified prediction graphs will make them more accurate, GIS should be considered as an alternative. GIS can be used to measure erosion rates over any time period that aerial photography is available, and along an entire stream system without the travel, weather or safety concerns. Other variables can be measured remotely as well, allowing comparison of the erosion rates to things such as vegetative cover, sinuosity and slope (see Chapter 3). For the purposes of this study, GIS was the preferred tool to measure erosion rate. The temporal and spatial scale were beneficial in determining background erosion rates, and searching for correlations with other larger-scale channel characteristics. The lateral erosion rates from these three streams, updated prediction graphs, and a comparison of results from three lateral erosion measurement tools can simplify erosion hotspot identification, and speed restoration implementation for land managers.

Chapter 3: The Effects of Vegetation Type and Channel Characteristics on Stream Lateral Erosion Rates

3.1. Introduction

As Americans cleared forests and prairies for agriculture, industry and homes, the watersheds contributed higher volumes of water and sediment to streams, which in turn became more erosive (Murgatroyd and Ternan, 1983). Altering the rivers to prevent flooding, allow more space for livelihoods and residential areas, and increase navigation also resulted in more erosive river systems. These actions and reactions have increased sediment loading to rivers. Sediment suspended in water, as well as algae and other light-scattering materials in the water column cause turbidity. It has been called one of the nation's leading water quality problems (Waters, 1995; Simon, 1999).

The erosion of the channel itself has been identified as a major source of a stream's turbidity load (Wilken and Hebel, 1982; Odgaard, 1984; Trimble, 1997; Bull, 1998; Walling et al., 1999; Simon, 2004; Wilkinson, 2009). Generally, the higher the flow, the higher the turbidity (MPCA, 2012b; Schottler et al., 2013); increased channel erosion has been linked to watershed land use conversions, removal of riparian vegetation, channelization, and river morphology (Hooke, 1980; Lawler et al., 1999; Zaimes, 2004; Rutherford, 2007; MPCA, 2012b). In agriculture-dominated watersheds, this rate has been tied predominantly to erosion of streambanks, bluffs and ravines (Sekely et al., 2002; Thoma et al., 2005; Wilson et al., 2008; Juracek and Ziegler, 2009; Schottler, 2010; Zaimes and Schultz, 2012).

Stream banks contribute 25 to 80 percent of stream sediment loading (Hamlett et al., 1983; Odgaard, 1987; Wilkin and Hebel, 1982; Simon et al., 1996; Bull, 1997; Lawler et al., 1999; Simon and Darby, 1999; Schilling and Wolter, 2000; Sekely et al., 2002; Amiri-Tokaldany et al., 2003; Evans et al., 2006; Zaimes et al., 2006; Fox et al., 2007; Sass and Keane, 2012). Non-field sources constitute less than 50 percent of stream sediment loading (Trimble, 1983; Fitzpatrick, 1999; Thoma et al., 2005; Johnson, 2009; Schottler, 2010; Lenhart et al., 2011b; Schottler et al., 2013).

Aquatic species have adapted their life cycles to a mosaic of flow velocities and depths, temperatures, water quality, dissolved oxygen, aquatic vegetation, and debris or overhanging structures (Wohl, 2005; MPCA, 2014; MPCA, 2012b). Channelization, inundation, and other alterations can dramatically reduce habitat variability, and therefore habitat quality and species richness (MPCA, 2014). Sediment suspended in waterways can diminish aquatic habitat by depositing on spawning grounds, blocking light from plants, impairing gill function, making hunting difficult for aquatic predators, and making water too erosive for inhabitants (Palmer and Allan, 2006; MPCA, 2012b; MPCA, 2014).

The suspended sediment can carry with it nutrients bound to eroded soils, further encouraging excessive algae and plant growth and decay, higher turbidity, lower water quality, and subsequent low oxygen, further diminishing habitat (MPCA, 2012b; MPCA, 2014; Palmer and Allan, 2006). Healthy riparian habitats are becoming rare, with 70 to 90 percent of vegetation lost or degraded, and 33 to 75 percent of aquatic species rare to extinct (Doppelt, 1993).

Vegetation plays a number of physical roles in determining bank erodibility. Plants intercept precipitation, decreasing the impact power; stems decrease overland flow velocity; roots bind soils and create infiltration pathways; and biomass presses down on the bank surface (Simon and Pollen, 2006; Osterkamp and Hupp, 2010; Camporeale et al., 2013). Camporeale et al. (2013) sampled 58 studies of the influence of vegetation on river morphodynamics, and classified the variables as flow field (friction factors, velocities, etc.), bank stability (erosion potential and bank height, root reinforcement, etc.), river erosion (erosion rate scenarios), morphological change (planform change, width change, channel form change, etc.) and sedimentation (over-bank sedimentation rate, sediment sorting index and accretion rate).

3.1.1. Influence of Vegetation Type on Erosion Rate

With vegetation playing a large role in the stability of banks and water quality of streams, the optimal species composition of managed buffer systems is important to understand. For example, vegetation stem density can make major changes to stream channel form, dimensions and velocities (Mackin, 1956; Hadley, 1961; Brice, 1964; Zimmerman et al., 1967; Nevins, 1969; Charton, 1978; Graf, 1978; Andrews, 1984; Hey and Thorne, 1986; Goodwin, 1996; Huang and Nanson, 1997; Rowntree and Dollar, 1999; Gran and Paola, 2001). In a large flume study, the addition of vegetation lead to sedimentation and cutoff of low-velocity channels, reducing the number of active channels. As vegetation density increased, the increased bank stability reduced velocity variability without speeding up the flow, lowered lateral erosion rates, narrowed and deepened channels, and increased channel slope (Gran and Paola, 2001).

When comparing bare soil, cropped, herbaceous, and forested stream banks, the erosion rates vary widely. Although, generally, the less-dense bare and cropped scenarios had the highest erosion rates. Several studies found a twofold to tenfold difference in erosion rates of bare ground versus vegetated reaches (Odgaard, 1987; Allmendinger, 2005; Beeson and Doyle, 1995; Micheli, 2002). Sass and Keane (2012) found three times less erosion in woody reaches than herbaceous reaches. Over a four-year period, Zaimes et al. (2006) found forested reaches had the least erosion at 0.2 meters (0.6 feet), pastures next at 0.59 meters (1.9 feet), and row crop fields the highest erosion at 0.64 meters (2.1 feet). Forest reaches had significantly lower erosion rates, reducing soil loss by 77 to 97 percent (Zaimes et al., 2006). Mean critical shear stress was two to three times lower in grass reaches than forested (Wynn et al., 2004).

Vegetation type is not a simple erosion variable, but rather an interconnected one. Vegetation can minimize the effects of freeze-thaw, by acting as an insulating blanket against temperature swings, thereby decreasing erosion rates (Abernathy and Rutherfurd, 1998; Wynn and Mostaghimi, 2006a; Wynn and Mostaghimi 2006b). Zaimes et al. (2006) found freeze-thaw was the primary erosion process: erosion pins showed sloughing of soil from high in the bank profile; when the deposition was washed away in the spring, the rate of erosion was comparable to peak discharge events. Freeze-thaw was the primary erosion process in Wolman (1959), Lawler (1986) and Stott (1997) as well Wynn and Mostaghimi (2006b).

Freeze-thaw events can limit the ability of vegetation to become established (Zaimes et al., 2006; Underhill, 2013). Wynn and Mostaghimi (2006b) found the winter daily temperature range and number of freeze-thaw cycles to be significantly higher beneath a forested canopy, compared to the much closer and denser herbaceous canopy; at two to three times and eight times, respectively. For the rest of the year, however, forests were much better at protecting soils against desiccating temperature swings than herbaceous canopy.

3.1.1.1. Influence of Vegetation Type on Bank Moisture

Drier banks are generally considered more stable than wet soils; and soil moisture is significantly dependent upon evapotranspiration and rooting patterns (Thorne, 1990; Abernathy and Rutherfurd, 1998). While woody and herbaceous communities remove moisture from the soil through transpiration, and allow infiltration through stemflow and macropore flow, the volumes of moisture removed differ. Simon and Collison (2002) found that beneficial or detrimental effect of vegetation on stream bank stability depends on antecedent rainfall; that the hydrologic effects of vegetation are as important as the mechanical effects.

Given wet and dry antecedent moisture conditions, Simon and Collison (2002) found trees increased the factor of safety by 32 to 46 percent mechanically (soil moisture modification, root reinforcement and weight), and 29 to 71 percent hydrologically (infiltration and transpiration). Grasses, on the other hand, increased factor of safety by 49 to 70 percent mechanically, and decreased factor of safety by 10 to 15 percent. In general, trees and grasses were both beneficial mechanically, but only trees were beneficial hydrologically to streambank stability.

Wynn and Mostaghimi (2006a) found herbaceous sites were generally drier, likely due to increased sun and wind exposure, and higher shallow evapotranspiration. Wynn and Mostaghimi (2006a) stated this drying effect may reduce critical shear stress in sandy soils. Simon and Collison (2002) found forested sites were generally drier, dried faster after precipitation, and maintained drier soil conditions into January and February, when moist soils are at risk of freeze-thaw damage. These sites had matric suction 40 to 60 kPa (5.8 to 8.7 psi) higher than other treatments. Despite maintaining a hydrologic advantage into the winter, Simon and Collison (2002) found most bank failures during winter and early spring, when transpiration is minimal or dormant, and high-intensity rainfalls fall through leaf-free canopies.

Simon and Collison (2002) found that the forested sites were briefly wetter than other sites, however, and explained this as increased infiltration capacity and a root-induced perched water table. This brief hydrologic decrease in factor of safety was offset by the mechanical strength of the tree roots. It bears pointing out that the minimum mechanical factor of safety in the forested site in this study was higher than the minimum mechanical factor of safety in the grassland site, when considering studies discounting trees based on surcharge. Surcharge is a normal stress, or weight acting on failure planes, and generally reducing shear strength (Simon and Collison, 2002). Simon and Collison (2002) found surcharge at 7 percent, which dropped mechanical factor of safety to the 32 to 46 percent range.

3.1.1.2. Influence of Vegetation Type on Sediment Transport, Stream Width

Another means of gauging erosion rates in streams is to measure sediment transport. Vegetation affects sediment transport and deposition (Prosser et al., 1995; Ishikawa et al., 2003), by affecting the flow field (Bennett et al., 2008). Trimble (1997) recommended removing woody vegetation to reduce sediment yield. The study found grassy reaches were narrower, and encouraged deposition of sediment, while forested reaches carried a greater local flux of sediment. Allmendinger (2005) also found higher deposition in nonforested reaches. McBride et al. (2008) explained that higher sediment loads in reforested reaches may be due to the channel widening, as it transitions from a narrower, grassy reach to a mature forest.

Many studies have found forested reaches are wider than herbaceous or grassy reaches (Zimmerman et al., 1967; Clifton, 1989; Sweeney, 1992; Peterson, 1993; Davies-Colley, 1997; Scarsbrook Halliday, 1999; Hession et al., 2000; Hession, 2004; Sweeney et al., 2004; Allmendinger, 2005, Roy et al., 2005). These streams may be as much as 2 to 2.5 times wider in forested reaches than herbaceous reaches (Zimmerman et al., 1967; Davies-Colley, 1997; Trimble, 1997; Hession et al., 2000). Conversely, several studies have found herbaceous reaches are wider than woody reaches (Charlton et al., 1978; Hey and Thorne, 1986; Rosgen, 1996; Gregory et al., 1988). Forest reaches can store more sediment behind accumulated organic debris, than they lose through channel widening (Keller and Swanson, 1979; Montgomery, 1997; Bilby and Bisson, 1998; McBride et al., 2008). Holding bank sediment constant, width-depth ratios decrease as vegetation density increases (Charlton et al., 1978; Andrews, 1984; and Hey and Thorne, 1986).

Murgatroyd and Ternan (1983) observed more active bank erosion in forested reaches, with widening and aggrading leading to channels over two times the size predicted by contributing area. These larger dimensions – up to ten times greater than non-forested reaches – were attributed to the suppression of turf grass, and flow diversion around large woody debris. Zimmerman et al. (1967) and Trimble (1997) agree with these drivers of forest erosion.

Wider forested reaches may be due to other factors including removal of woody vegetation (Stromsoe and Callow, 2012), colonization of a riverbed by woody vegetation (Wende and Nanson, 1998; Tooth and Nanson, 2000; Pietsch and Nanson, 2011), and evolution from single to braided channel (Smith, 2004). McBride et al. (2007, 2008, 2010) finds small, forested streams are wider than small, nonforested reaches, but narrower in large streams (with contributing areas greater than 10 to 100 square kilometers; or 2,471 to 24,710 acres), and suggests that other studies may not be looking at a long enough time scale. Widths of streams with catchments over 15 square kilometers (3,707 acres) were not as heavily influenced by vegetation (Murgatroyd and Ternan, 1983).

McBride et al. (2008, 2010) created a channel evolution model describing the transition streams make in response to reforestation. The model begins with an herbaceous-species dominated reach, with a small, stable channel that easily overtops its banks (connected to its floodplain). As small woody plants sprout and grow, the bank roughness increases, altering floodplain hydraulics by reducing the speed of flood waters outside of the channel. The in-channel flood flow velocity remains the same however, increasing turbulence at this interface and therefore increasing scour. The scour spreads into bed degradation. The channel widens and deepens, sinking away from its floodplain. As the woody plants mature and begin shedding branches or falling entirely into the stream, grasses are outcompeted, and the surcharge (weight) on banks increases. The final, forested product is wider, slower (with more in-stream roughness) and has a richer habitat compared to the grass system. Murgatroyd and Ternan (1983) and Montgomery (1997) also found forested reaches with greater variability in channel width, and credited the inconsistency with a richer habitat, induced by a range of flow depths, velocities and substrate sizes.

This widening process begins slowly – Davies-Colley (1997) found pine plantations began widening 18 years after reforestation, and Parkyn (2003) found no widening within 24 years of reforestation – but accelerates as woody vegetation matures, with the most significant widening occurring 30 to 40 years after forests develop (McBride et al, 2008, McBride et al, 2010). The lag prior to significant widening may be explained by the time required for commonly credited erosion factors to develop – for woody vegetation to grow, shade out the herbaceous layer, create a rough floodplain, and contribute debris to the channel (McBride et al., 2010). A new stable state may take decades or a century without other disturbances (Davies-Colley, 1997; Trimble, 2004; McBride et al., 2008). Given this, McBride et al. (2010) recommended any stream restoration work take into account morphological changes which may occur over many decades following, and in response to plantings. McBride et al. (2010) cautions that bank erosion and erosion rates should not be directly compared with their stream widening results. However, it is difficult to determine if many other studies are measuring channel erosion or channel widening.

3.1.1.3. Influence of Vegetation Type on Response to Flooding

The size and density of floodplain vegetation has been reported to have an effect on the erosiveness of flood flows. When a stream escapes its banks, the flow velocity slows as it moves through floodplain obstacles. The stiffer and denser the obstacles, the "rougher" the floodplain, and the slower the flow. The discrepancy between the faster in-channel flow velocity and slower floodplain flow velocity creates turbulence along the interface of the two flow speeds – at the bank, where the vegetation grows (Rood et al., 2014; McBride et al., 2007). A small reduction in velocity can create a greater reduction in erosion, because boundary shear stress is proportional to the square of near-bank velocity (Camporeale et al., 2013).

McBride et al. (2007) showed this near-bank velocity gradient in a flume study, finding forested reaches (high roughness) experience high turbulence, which enhances sediment entrainment and transport. McBride et al. (2007) concluded that this turbulence along the bank might explain why forested reaches can be wider than grass (low roughness) reaches, and recommends its addition to scour around large woody debris and shading of the herbaceous layer as the three major factors in forest versus grass erosion rates.

The following year, however, McBride et al. (2008) found scour around large woody debris and canopy shading of grassy vegetation were not the primary drivers for channel widening in their study area. The presence or absence of grassy vegetation, and volume or count of large woody debris did not appear correlated to the amount of channel widening.

While the interplay between the flooded channel and its rough banks may accelerate erosion, the roughness of the floodplain induces deposition of entrained sediment. Sedimentation rates are higher among vegetation, and is dependent on stem diameter, distance from the bank, and flood duration (Hickin, 1974; Nanson and Beach, 1977; Steiger et al., 2001a; Steiger et al., 2001b). The herbaceous reaches eroded on average 24 meters (79 feet) during a 1993 Kansas flood, while forested reaches experienced soil deposition (Geyer et al., 2000). Beeson and Doyle (1995) found nonforested reaches experienced 30 times the bank erosion of forested reaches.

The effect of floodplain roughness may be most evident in Rood et al. (2014), which studied the reaction of forested and grassland reaches to two major floods. Rood et al. (2014) found grassland was extensively scoured (over 75 meters; over 246 feet), regardless of sinuosity, but forests minimized scour, essentially stopping near the treeline (under 15 meters; under 49 feet). An area covered in grass and extensively scoured in the first subject flood, largely avoided erosion during the subsequent flood, which Rood et al. (2014) attributed to the juvenile cottonwood grove, which grew in the interim.

Grasslands may be better at slowing near-bank velocities and therefore erosion than trees in smaller systems with lower velocities, but as size and velocity increase, the floodplain roughness, large woody debris (channel roughness), and root system of forests becomes more important (Camporeale et al., 2013; Rood et al., 2014). It is possible that big plants, such as trees, are best at resisting the larger floods (Hawkins et al., 1997; Griffin and Smith, 2004; Vincent et al., 2009; Collier and Quinn, 2003; Rood et al., 2014). Collier and Quinn (2003) for example, found channel widening four times wider in pasture than forest.

The combination of afforestation initially widening channels, but later stabilizing and resisting erosion, may allow it to carry higher flows. Murgatroyd and Ternan (1983) observed no overbank or bankfull discharges over a five-year period in forested reaches, but during the same time observed on average two to three overbank events per year in non-forested reaches.

3.1.1.4. Influence of Vegetation Type on Rooting Pattern

Of all vegetation's influences on stream stability, the most important may be in the form of roots (Abernathy and Rutherfurd, 1998). Soil shear strength increases linearly with root biomass density (Micheli and Kirchner, 2002). The strength roots lend to streambanks has been tested a number of ways, by many researchers; some with an eye towards determining if trees or grasses provide the best support. The testing method, species, soils and hydrology are a factor in each conclusion.

Dunaway et al. (1994) found plant roots on alluvial streams provide an important interlocking mesh, given an inversely proportional relationship between erosion rate, and root length and volume. The relationship between root diameter and root strength is less clear (non-linear and inverse): Simon and Collison (2002) found literature tended to conclude this diameter-strength relationship meant dense herbaceous species were the best erosion control choice. Murgatroyd and Ternan (1983) found thick turf grass was superior to spruce trees, based on much higher root density and ground cover, in resisting lateral erosion.

Wynn et al. (2004) looked at rooting density through the lens of root length density (RLD is the total length of roots in a unit of soil, independent of root size) and root volume restriction (RVR is the total volume of roots in a unit of soil), excluding roots over 20 millimeters (0.8 inches) in diameter (to avoid the natural RVR bias towards larger roots), and sampling areas at least 30 centimeters (12 inches) from tree trunks.

Wynn et al. (2004) found 55 percent of all tree roots occurred within the top 30 centimeters (12 inches) of soil; while 75 percent of all herbaceous roots occurred within the top 30 centimeters (12 inches) of soil. In this upper region, herbaceous sites had significantly greater root length density than forested sites. Other studies showing tree roots at 43-74 percent and grass at 50-79 percent in the upper layer (Davidson et al., 1991; Shields and Gray, 1992). In the top 30 centimeters (12 inches), trees had 55 percent of their RLD, and 41 percent of their RVR. Grasses had 75 percent of their RLD and 74 percent of their RVR (Wynn et al., 2004).

Ninety percent of all roots were found within the top 17 centimeters (7 inches) for eastern gamma grass, 32 centimeters (13 inches) for black willow, 38 centimeters (15 inches) for sweetgum, 56 centimeters (22 inches) for river birch, 67 centimeters (26 inches) for switchgrass, and 74 centimeters (29 inches) for sycamore; all with most reinforcement concentrated in the upper 50 centimeters (20 inches) of soil (Simon and Collison, 2002).

In the top 15 centimeters (6 inches), herbaceous species had 20 percent more fine roots (0.5 to 2.0 millimeters, or 0.02 to 0.08 inches) than forest species. Below 15 centimeters (6 inches) and the bank profile as a whole, forested species had greater overall root volume (again measuring only roots under 20 millimeters, or 0.8 inches). At all depths, herbaceous species had more very fine roots (under 0.5 millimeters, or 0.02 inches). (Wynn et al., 2004)

Forested sites were dominated by fine roots (0.5 to 2.0 millimeters, or 0.02 to 0.08 inches). Herbaceous sites were dominated by very fine roots (under 0.5 millimeters, or 0.02 inches). Wynn et al. (2004) concludes that forest species may provide the best bank protection for several reasons: 1. Research has established a direct relationship between erosion resistance and fine root density, a class size dominated by tree species; 2. By producing significantly greater root length and volume below 30 centimeters (12 inches), forest species may provide better protection against stream bank scour where hydraulic shear stress is greatest – at the toe of the stream bank. Root density was a significant factor in soil erodibility, but presence of roots did not influence soil critical shear strength in Wynn and Mostaghimi (2006a). Simon and Collison (2002) generally agrees when stating reinforcement with depth is important, because when roots are concentrated, and mostly limited to the upper 20 centimeters (8 inches) they can allow soil to shear off at the root boundary, obviating the reinforcement effect.

Simon and Collison (2002) found tree roots increased soil strength by 2 to 8 kPa (0.3 to 1.2 psi), and grass roots increased soil strength by 6 to 18 kPa (0.9 to 2.6 psi). The strongest roots of the study were from switch grass, which Simon and Collison (2002) says is due to root area ratio, rather than root strength. Controlling for the effect of diameter on tensile strength, the roles reverse, with sycamore roots strongest (45 MPa, or 6,527 psi), river birch (22 MPa, or 3,191 psi), sweet gum (18 MPa, or 2,611 psi), gamma grass (17 MPa, or 2,466 psi), black willow (13 MPa, or 1,885 psi) and switch grass last (8 MPa, or 1,160 psi). This illustrates the understanding that grass root systems are strong by way of a dense network of small diameter roots, one to two times denser than trees; and trees have significant root tensile strength (Simon and Collison, 2002).

Simon and Collison (2002) finds that the greatest strength lent by woody species' roots is from a relatively small number of large (over 0.5 millimeters, or 0.02 inches in diameter) roots. Furthermore, Simon and Collison (2002) concludes root area in woody species is generally more important than strength, as root area allows the greatest cohesion. Piercy and Wynn (2008) states root size and density are a better measure of root stress and bank stability.

Underhill (2013) went on to observe no correlation between root density, and type of vegetation, with herbaceous, shrub and forest dominated reaches each contributing similar root density to streambanks.

3.1.1.5. Influence of Large Woody Debris and Stream Size

Large woody debris is a major contributor to the difference between forested and non-forested lateral erosion (Murgatroyd and Ternan, 1983; Abbe and Montgomery, 1996; Montgomery, 1997; Trimble, 1997; Abbe and Montgomery, 2003; Jeffries et al., 2003; Allmendinger et al., 2005; Brummer, 2006). Large woody debris is rather self-explanatory, including whole trees, and large portions thereof. The debris can fall into streams at any time, most notably during flood and storm events. When blown in, they experience windthrow. If attached to the soil, the fall will deliver a portion of the bank into the stream. Once in the stream, the large woody debris alters flow paths and velocities.

The flow path and velocity alteration can be beneficial or detrimental. Trees tumbled in floods tended to align with the existing channel flow, which can protect banks from scour, and initiate island building (Harmon et al., 1986; Nakamura and Swanson 1993; Abbe and Montgomery, 1996; Abbe and Montgomery, 2003; Rood et al., 2014;). Camporeale et al. (2013) noted the debris and the sediment that accumulates behind it can create benches, which further aggrade to establish a local floodplain. The debris can locally reconnect an incised channel to portion of its floodplain, deflect flows against more susceptible banks (Shankman, 1993), induce avulsions (Camporeale et al., 2013), or colonize to eventually support the oldest stands of floodplain forest on an erosion-resistant base (Montgomery and Abbe, 2006; and Collins et al., 2012).

Then again, there may not be an observable alteration. McBride et al. (2008) did not find a correlation between large woody debris and channel widening, or greater scour near individual debris or debris jams. Windthrow quickly becomes unimportant as the channel size increases (Abernathy and Rutherford, 1998).

A tree fallen into a large stream may stabilize banks, but the same tree in a small stream may accelerate flow and scour banks (Thorne, 1982; Camporeale et al., 2013). The vegetation most suitable to reduce erosion may be dependent upon stream size. As the channel outgrows the vegetation size, the effect the vegetation has on hydraulics decreases (Thorne and Furbush, 1995). Grasses can minimize erosion rates best in headwaters, especially given the lack of windthrow, and its ability to insulate and protect against subaerial preparation (Nanson and Hickin, 1986; Camporeale et al., 2013; Underhill, 2013). Granted, Abernathy and Rutherfurd (1998) found deep-seated rotational failure common along lower and less-steep grassy banks. Medium-sized vegetation may be best at protecting medium-sized streams: Underhill (2013) found thick, deep-rooted shrub communities were best at reducing erosion from fluvial entrainment. Larger streams, with larger bank heights may benefit the most from the deepest rooting plants: trees. Underhill (2013) noted the larger river reaches dominated by woody vegetation had the lowest erosion rates.

3.1.2. Influence of Channel Characteristics on Erosion Rate

As this study was GIS-based, the remainder of the variables collected were taken from the suite available to GIS users. Related to, and partially covered by the erosion and vegetation studies above, additional variables measured included eroded area, reach length, valley length, sinuosity, water surface slope, low bank slope, high bank slope, water surface elevation, low bank elevation, high bank elevation, low bank height, high bank height, bankfull width, radius of curvature, near bank stress, stream mile (size), curve count, curve length, wetland presence, geomorphology, soils and erosion to bankfull ratio.

These channel characteristics are interrelated, and play a role in the energy movement and form of streams. The bankfull width, depth, height, slope, sinuosity and meander arc length are among the nine degrees of freedom identified for channel movement (Hey, 1997). The USGS (1962) also credited slope and width, and added depth, velocity, sediment load, sediment size, hydraulic roughness and discharge to the list of channel-forming variables.

Other relationships include that of longitudinal profile to width, slope, depth, discharge, load, size of debris, flow resistance and velocity; a linear relationship between meander length, radius of curvature, bankfull width and amplitude (Leopold et al., 1992); and an empirical relationship between meander length and the square root of bankfull discharge (Leopold et al., 1992). Factors most affecting channel characteristics are also nearly dependent, and include slope, width, velocity and depth (Leopold et al., 1992). Nanson et al. (1975, 1983, 1986) stated a clear connection between bank erosion and bend curvature, reaching a maximum erosion rate with a curvature ratio near three. Erosion, it was explained, attempts to maintain a minimum curvature (Nanson and Hickin, 1986).

USDOT (2012) finds the potential for scour increases with depth, and depth increases with stream size, so the potential for scour increases with stream size. USDOT (2012) extends this to connect potential for lateral erosion with stream size, noting that there are many ways of measuring stream size, such as watershed size, flow rates, and channel dimensions. Some research suggests a connection between erosion rates and bankfull widths, with streams moving 1 to 2.5 percent of their widths per year (or 1 to 2.5 channel widths per century) (Nanson and Hickin, 1986; FHWA, 1978; Walker and Rutherfurd, 1999).

Simon and Pollen (2006) lists bank height and slope, the weight of soil and water within it, and surcharge (weight) as driving forces for bank instability. A larger distance between the soil surface and groundwater (taller banks) can allow trees and plants to grow denser, with deeper roots, aiding in resistance to temperature and moisture related damage by insulating and withdrawing more soil moisture, as well as windthrow (Abernathy and Rutherfurd, 1998; Crow, 2005; Underhill 2013). Addition of herbaceous species to a wet meadow (wetland) riparian zone creates a dense layer of very fine roots, which increases soil shear strength by up to eightfold (Micheli and Kirchner, 2002). An undercut can be ten times deeper yet withstand erosion, if it is reinforced by wet meadow (wetland) riparian vegetation (Micheli and Kirchner, 2002). Granted, bank height may have no effect on erosion rate, as found by Nanson and Hickin (1986).

3.1.3. Objectives

The project objectives were to:

1. Measure erosion rates across multiple vegetation covers to determine whether woody or herbaceous species are better at stabilizing stream banks against lateral erosion; and
2. Collect GIS-measurable channel characteristics commonly cited as potential lateral erosion variables to assess correlations.

3.2. Materials and Methods

3.2.1. Tools and Statistics

3.2.1.1. Lateral Erosion

Lateral erosion generally occurs as the laterally sloping bed near an outside bank is scoured by fluvial erosion, the unsupported portion falls in a mass failure event, and the resulting debris is swept downstream before the process repeats (Thorne, 1990; Burkhardt and Todd, 1998; Nanson and Hickin, 1986; Simon and Collison, 2002). The inside curve receives sediment deposits, which are colonized each growing season by riparian vegetation, allowing the advancing inside curve to slowly chase the receding bank (Leopold, 1962; Burckhardt and Todd, 1998). As opposed to longitudinal erosion, which is generally the movement of the wavelength of bank curves downstream, lateral erosion is associated with a change in river belt or amplitude of curves, depth, slope and bankfull width (citations). Several methods of measuring lateral erosion were explored in Chapter 2. This chapter relies on a set of tools developed by Mark Ellefson (2015) to be used with ESRI's ArcMap Geographic Information System (GIS) software.

Two high-quality, orthorectified aerial photography sets are required to measure lateral erosion with GIS. Due to photography technology improving over time, more recent photography was used in this study. The goal was 1991 to 2010 for each of the three river systems, for a 19-year range (2011 onward were not yet available). An 8-kilometer (5-mile) section of the Whitewater River was restored in the 1990s, and subsequent poor visibility photography sets limited the Whitewater River range to 2003 to 2010.

A centerline was drawn down the middle of each channel in each year. A single buffer size was chosen to cover the three channels at their widest, with at least 35 meters (115 feet) on either side. A 60-meter (197-foot) buffer was therefore drawn around each centerline using the ESRI buffer tool (creating a 120-meter, or 394-foot wide polygon centered along the stream). This buffer width was chosen to partially to reflect current understanding of how wide a buffer might be to impact water quality, but primarily to provide consistent coverage for three channels from top to bottom.

Figure 25: Buffer width and centerlines from two years of aerial photography

The user defines reach lengths, or distances over which the lateral erosion will be measured. As the primary goal of this research was to determine if predominance of woody or herbaceous species influenced erosion rate, reaches were based on cover type. ESRI's cut polygon tool was used to cut each stream's buffer polygon perpendicular to the stream flow where cover class changed.

Each of the streams was now segmented into a series of reaches in need of data. The goal of the DNR Static Lateral Migration Tool was to prepare data to enable the ESRI feature to polygon tool to output erosion rates (Ellefson, 2016). Feature to polygon turns the spaces between intersecting lines into polygons. In this case, the spaces between intersecting lines, or changes in stream centerline over the years, is eroded area. Numerous issues, such as breaking a stream into reaches, can leave loose ends, or open polygons, which the ESRI tool will not view as a polygon, and therefore not count as eroded area.

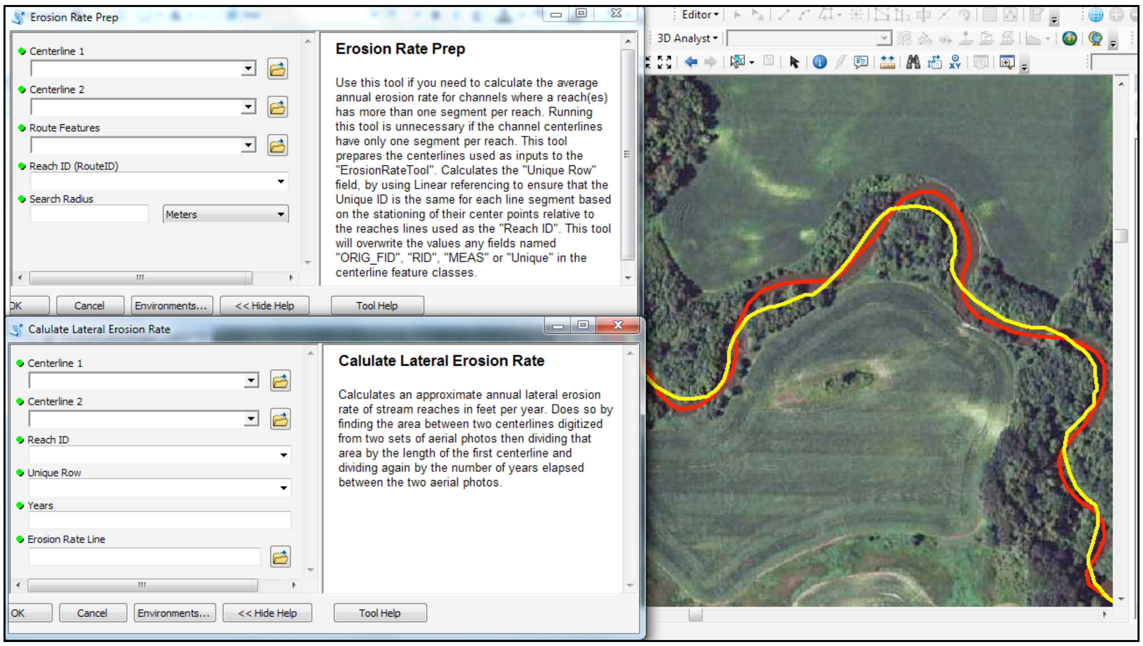

Figure 26: DNR Static Lateral Migration Tool (Ellefson, 2015)

To ensure this string of polygons is useful as a measure of eroded area (and later erosion rate), DNR Static Lateral Migration Tool's "Erosion Rate Prep" ensures every appropriate reach forms a closed polygon (no open ends as graphic above illustrates). It assigns markers along the first centerline, which it matches to markers along the second centerline using linear referencing. It uses ArcGIS "Route Features" to incorporate reach breaks, which intersect the pair of centerlines. It runs an error check to ensure the markers line up and polygons are closed, runs ArcGIS "XY to Line Tool," and ArcGIS "Feature to Polygon" tool. Next, DNR Static Lateral Migration Tool's "Calculate Lateral Erosion Rate" calculates the area of each polygon, divides it by the length of the first centerline, and divides it by years between centerlines to convert eroded area to lateral erosion rate (Ellefson, 2016).

The erosion rate should be viewed as an upper limit, as line segments that do not form polygons are not counted toward the total erosion. Its accuracy is limited by the accuracy of the aerial photography and its user. A strength of this tool is comparison of erosion rates between reaches. (Ellefson, 2016).

Figure 27: Lateral erosion: pink illustrates the eroded area between centerline years.

3.2.1.2. Stream Mile (Size)

ArcMap assigned a unique number and recorded reach length as each successive buffer cut was created, moving from one end of the stream to the other. It recorded these numbers by default as the centerline was broken by cover type. The size of reaches was based entirely on changes in cover type, as the driving question of this research was whether there was a discernable difference in erosion rate between vegetation categories.

The more changes in cover, the higher the reach number. Elm Creek was divided into 119 reaches over 172 kilometers (107 miles). The Buffalo River study section was divided into 109 reaches over 132 kilometers (82 miles). The Whitewater River study section was divided into 11 reaches over 29 kilometers (18 miles). Reach numbers and lengths were interesting because they could be used as a coarse approximation of stream mile (a standard distance counted from headwater to mouth), by adding successive reach lengths, and a coarse approximation of stream size (streams typically increase in size as they move from headwater to mouth). While not enabling the comparison between stream systems, the reach number, stream mile and stream size data could be compared to other variables along the same stream channel.

3.2.1.3. Cover

Cover is types and densities of vegetative communities, as viewed on aerial photography. The stream buffer polygon was broken when vegetation cover changed between established categories. These cover changes often occurred along property and field lines, reflecting changes in land use.

No coverage percentages were found in literature review of vegetation effects on stream erosion, so four categories were created based on the most obvious visual breaks. Density pattern charts (Munsell Color, 2010) were used to ensure accuracy and uniformity of cover classes. From most herbaceous to most woody, the cover classes were Cover 1: grass with under 20% trees, Cover 2: grass with 20 to 40% trees, Cover 3: mixed with 40 to 80% trees, and Cover 4: forested with over 80% trees. As the cover types are based on aerial imagery and density of tree canopy, Cover 3 was considered "mixed" given the possibility that substantial grass communities could exist under the canopy. The length of each reach was summed by cover type for a total distance by cover type, and compared.

Figure 28: Cover 4 and Cover 1. On the left is Cover 4 (forested with over 80% trees) and on the right is Cover 1 (grass with under 20% trees). A reach break was created at the edge of the forest, near the center of this image (orange). The lines are the centerlines from two different aerial photographs used for erosion rate calculations.

Figure 29: Cover 2 (grass with 20 to 40% trees)

Figure 30: Cover 3 and Cover 4. On the left is Cover 3 (mixed with 40 to 80% trees), and on the right is Cover 4 (forested with over 80% trees). The reach break is again illustrated in orange, with Cover 3 shaded yellow and Cover 4 shaded green. Note: the south half of the stream is field, and the north half is forested. It was somewhat common to find one bank in a different land use than the other.

3.2.1.4. Sinuosity

Sinuosity is a measure of how long a stream's path is from one position on the landscape to the next; it measures how curvy or straight the channel is. Reach length was measured along the stream's path (numerator in the equation above), and valley length was measured as a direct line from one end of a reach to the other (denominator in the equation above), using the GIS measure tool. Sinuosity was recorded after dividing reach length by valley length.

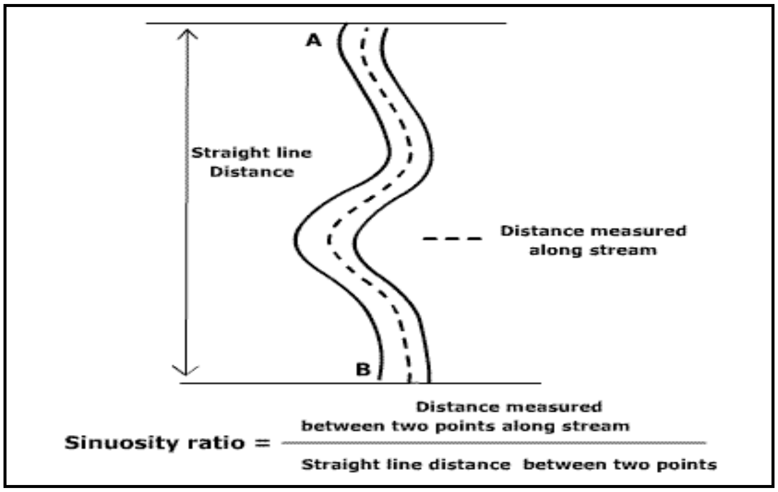

Figure 31: Sinuosity measurement (MichiganTech, 2016)

A perfectly straight channel has a sinuosity of 1 (no deviation between the shortest distance between two points and the stream's path). A sinuosity under 1.2 is considered low sinuosity (Rosgen, 2008). Moderate sinuosity is above 1.2 but below 1.5 (Rosgen, 2008). Highly sinuous reaches are 1.5 at the lowest, but can reach much higher values (called "tortuous") when a stream travels a long distance between two relatively close points.

3.2.1.5. Near Bank Stress, Curvature, Bankfull

Near bank stress has been identified in several studies as a variable in erosion rates (Kean et al., 2009; McBride et al., 2007; Hopkinson and Wynn, 2009). Near bank stress is a measurement of the force a stream exerts near its banks, using velocity profiles and energy distribution. These measurements are generally taken along the outside bend of a stream, where velocities are greatest.

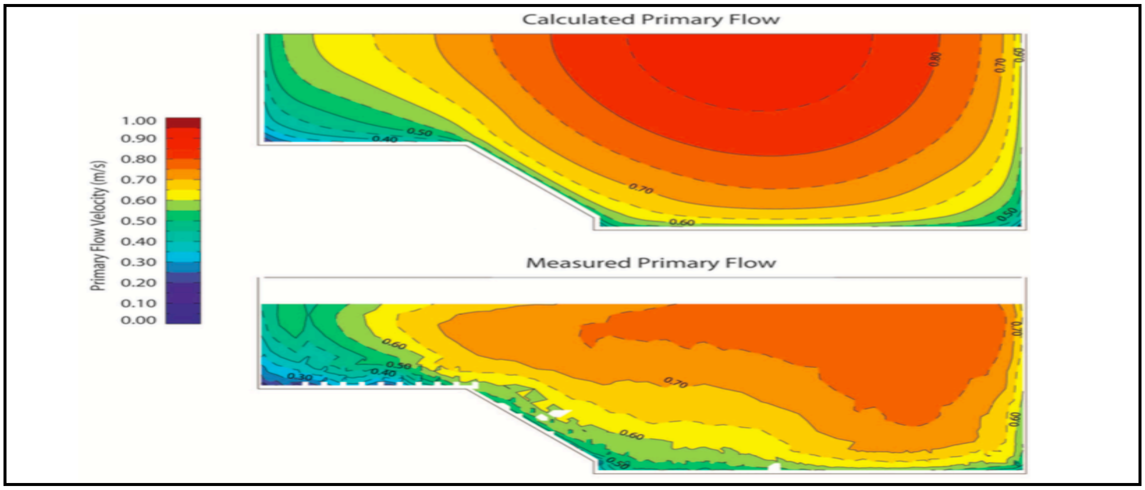

Figure 32: Velocity profiles (Kean et. al, 2009)

While the most accurate near bank stress values require equipment to measure velocity at various depths, there are fortunately several simpler means of estimating near bank stress. Table 4 lists near bank stress methods. A number of these methods are available to GIS users. Method 2 (radius of curvature divided by bankfull width, Table 4) was chosen for this study. It allows for measurement of near bank stress at curves across three watersheds, without going to visit each. Using Method 2, near bank stress values are low when radii of curvature are low and bankfull widths are high. However, low near bank stress values translate into high near bank stress ratings (an inverse relationship between values and ratings, Table 5).

Table 5: Near bank stress measurements (Rosgen, 2008)

Methods for Estimating Near-Bank Stress (NBS)		
(1) Channel pattern, transverse bar or split channel/central bar creating NBS... ..	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf}) ...	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf}) ..	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf}).	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient	Level IV	Validation

Table 6: Near bank stress (Rosgen, 2008)

Converting Values to a Near-Bank Stress (NBS) Rating							
Near-Bank Stress (NBS) ratings	Method number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N / A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N / A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N / A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Radius of curvature is the numerator of the near bank stress equation used. Radius of curvature is the radius of the arc that best fits the bend in the stream channel. A small radius of curvature means a tight bend, which may put additional stress on a stream bank as water moves through. The more sinuous a stream, the more radii the user must measure. Fortunately, several highway departments have tools to measure curvature.

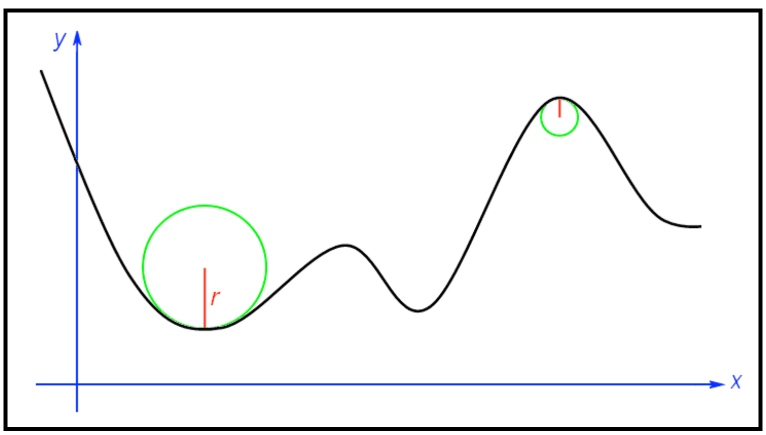

Figure 33: Radius of curvature (Kiatdd, 2016)

Roadways and streams have a few commonalities. Some dimensions (radius of curvature, slope, width, etc.) measured for traffic flow safety are also measured for stream flow erosivity. Tools reviewed by Rasdorf et al. (2011) and Findley et al. (2012) include field surveys, Curve Calculator (ESRI, 2010), Curve Finder (Harping, 2010) and Curvature Extension (FDOT, 2010).

When compared to field surveys and GIS linework of road centerlines, all three platforms were quite accurate, with Curvature Extension the best at 100 percent accuracy at matching GIS linework (Rasdorf et al., 2011; Findley et al., 2012). Of the available platforms, Curvature Extension was chosen for this research.

Curvature Extension was applied to GIS linework of stream centerlines to generate several measurements, including radius of curvature. Each curve of each stream over approximately 12 meters (40 feet) in diameter was measured and recorded, before averaging the radii by reach. To reflect the relative straightness or sinuosity of streams, an attempt was made to capture every radius of curve visible (small curves had small radii, straighter sections could have quite large radii).

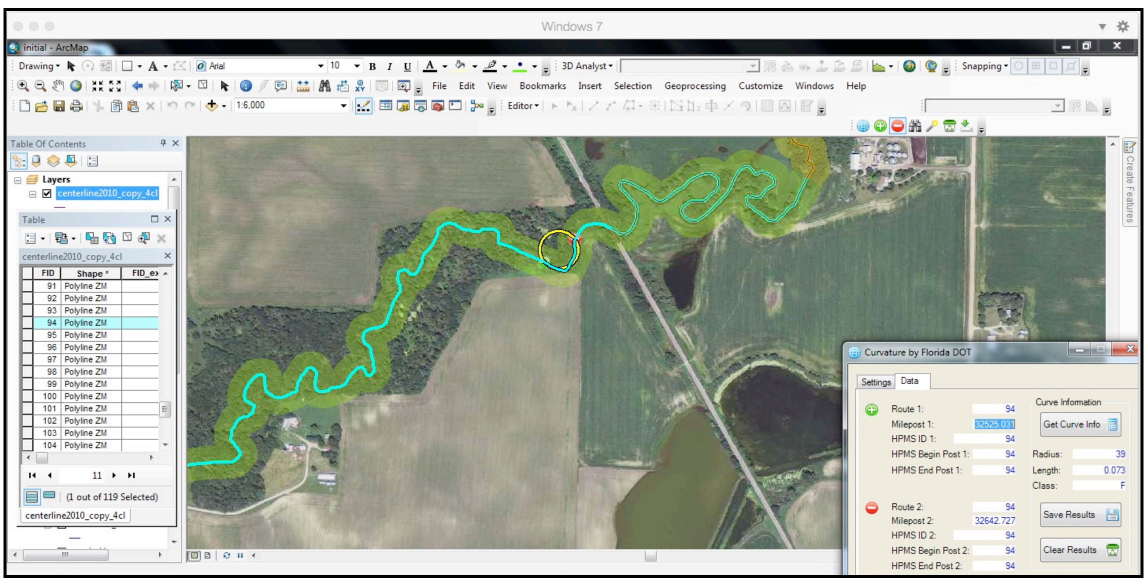

Figure 34: Curvature Extension, Elm Creek

In addition to radius of curvature per curve and averaged per reach, the number of curves per reach was recorded. Curvature Extension automatically generates several other variables, including curve length. This too was recorded for each individual curve, and averaged by reach.

Bankfull width is the denominator of the near bank stress equation used, but is also recorded as a possible variable in erosion rate. Bankfull is a standard stream width measurement, and considered a stream's natural breadth. It is the size of the stream at its dominant channel-forming flow volume, which has a typical recurrence interval of one to two years (Leopold et al., 1992). The extent of bankfull is visible as a change of scouring, topography, vegetation, soils and/or a litter line. Below this level, the channel is typically quite active, and above it the banks and floodplain are somewhat more stable. Bankfull width was measured using the ESRI measure tool at numerous riffle sections along each reach and recorded individually, and reach-averaged. The bankfull width was compared to the erosion rate to determine whether these streams fell within the range of migration found in literature.

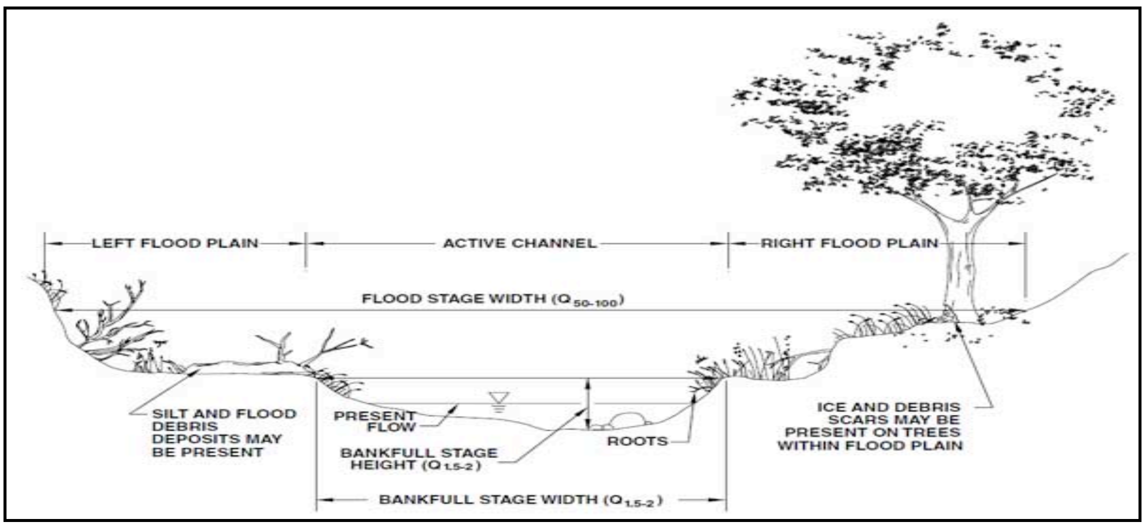

Figure 35: Bankfull (USFS, 2016)

3.2.1.6. Elevations and Slopes of Water Surfaces and Banks

Water surface elevation and slope was created for each reach of each stream using a mix of standard ESRI and custom Ellefson GIS tools (Ellefson, 2015). ESRI's Interpolate Shape tool extracts DEM elevations and assigns them to reaches in a digitized stream centerline. Ellefson’s Flatten Profile tool removed unwanted noise (such as road crossings and bridges) from the stream elevation data. Ellefson’s Calculate Slope tool used a sum of squares linear regression to attribute water surface slopes.

Bank height, elevation and slope came from Ellefson as well (Ellefson, 2015). At a user-specified distance, Ellefson’s Calculate Slope creates a right and left bank line on either side of, and parallel to, the stream centerline. The vertices of the centerline are snapped to the bank lines. Elevations are extracted from the DEM and stored in the vertex points. Ellefson’s Calculate Low Bank saves the lowest elevation recorded among the vertices of each reach. Ellefson’s Calculate High Bank saves the highest elevation.

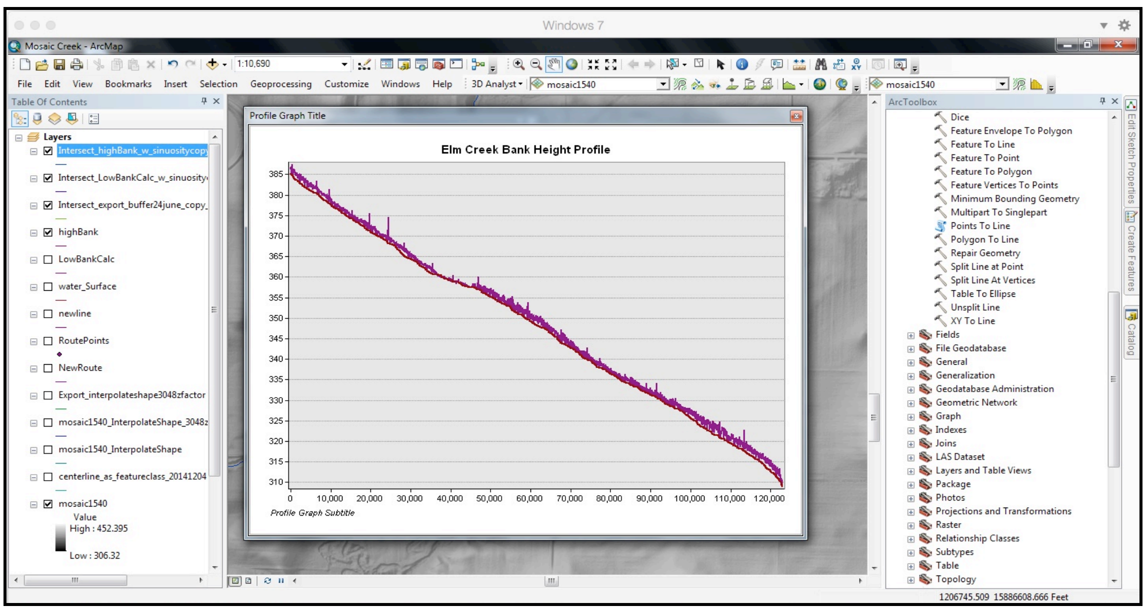

Figure 36: Bank heights profile before flatten profile

3.2.1.7. Stream Power

Stream power is the force of water acting upon its bed and banks, associated with potential to scour its channel and transport sediment. It is given by the equation:

$$\omega = \rho g Q S$$

where ω is stream power, ρg is the specific weight of water (product of ρ, the density of water (1000 kg/m^3) and g, the gravitational force (9.8m/s^2)), Q is discharge (m^3/s) and S is channel slope (m/m). All of the variables in the above equation are constants, or readily available through remote sensing, except discrete, reach-by-reach discharge values. Leopold and Maddock (1953) found discharge is a linear function of substrate erodibility constant (c) and watershed area (A):

$$Q = cA$$

Substituting for discharge, stream power becomes a function of the specific weight of water (ρg), substrate erodibility (c), and watershed area (A).

$$\omega = \rho g c A$$

Watershed area can be determined in GIS by hydroconditioning a watershed-wide digital elevation model (DEM). Hydroconditioning basically creates a DEM with bridges, roads and other digital stream dams removed: it allows GIS tools to visualize the stream as flowing under things, rather than ponding upstream of them. Once the DEM represents real-world stream flow, it can be used to determine watershed area at discrete locations, and therefore stream power at discrete locations.

Stream power was thoroughly vetted as a possible variable to add to this study, but based on estimates of labor required to hydrocondition three watersheds of this size (approximately 2025 to 4050 hours), it was eliminated as a possibility (Vaughn, 2015; Hall, 2015; Wick, 2013).

3.2.1.8. Wetland Presence, Soils and Geomorphology

Presence or absence of wetland was considered during the course of this study, but available National Wetlands Inventory (NWI) did not appear a reliable indicator of wetland locations. It was U.S. Fish and Wildlife Service policy to omit wetlands from NWI which were or may be farmed, commonly omitting wetlands within floodplains (USFWS, 1993), leaving riparian wetlands in agriculture-dominated wetlands especially under-reported. As all three of these wetlands were agriculture-dominated, the NWI would be lacking in each watershed. An aerial review of wetland signatures on Buffalo River revealed the wetland boundaries were sometimes difficult to delineate on the heavy soils, especially without the NWI to act as a back-up, and those boundaries did not line up well enough with vegetation reach breaks (one small wetland could flag the entire reach as wetland, see Figure 37) to warrant further investigation. This variable was removed from consideration.

This study considered comparing soils per reach for possible changes in erosion rates, but found the soil lines were not conducive for such reach-by-reach comparison. Soil type was therefore removed from consideration.

Geomorphology was also considered as a variable to note, but the geomorphology GIS layers available were not detailed enough for a reach-by-reach comparison of the study areas. For example, the attributes table of the geomorphology layer for the Buffalo River study area reported lacustrine or fluvial alluvium for the entire study area.

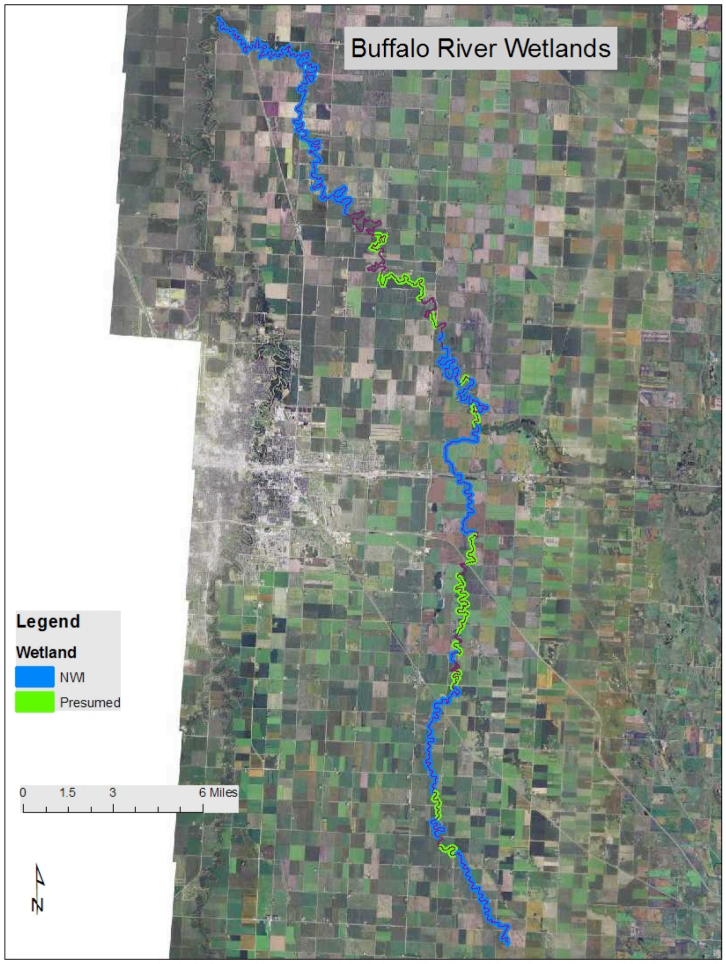

Figure 37: Reaches with wetlands identified by NWI (in blue) and additions by author (in green). Only purple reaches had no obvious wetlands.

3.2.1.9. Statistics

Erosion data were reviewed for correlations with other GIS-measured variables. After reviewing the data for normalcy, they were reviewed via basic statistics (minimum, maximum, median, mean, geomean, variance, standard deviation), boxplots (maximum, third quartile, mean, first quartile, minimum), Spearman rank correlation and Pearson product-moment correlation matrices, with linear regression on the most related. Those with a value under 0.2 were assumed to be not correlated.

Spearman rank correlation was used after the data were determined to be not normal. This method ranks data before using the difference in rank to define r. Each variable was compared to lateral erosion rates. Those variables most closely related to lateral erosion rates were closest to +1 or -1.

Formula for Computing the Spearman Rank Correlation Coefficient

$$r_s = 1 - \frac{6\,\Sigma d^2}{n(n^2 - 1)}$$

where
d = difference in ranks
n = number of data pairs

Figure 38: Spearman rank correlation coefficient formula (Bluman, 2011)

Nonparametric statistics is not necessarily better than parametric statistics (Bluman, 2011), so the data were also tested using the parametric Pearson correlation coefficient. A value of r near +1 or -1 indicates a strong linear correlation between lateral erosion rate and the variable it is compared to.

Formula for the Correlation Coefficient *r*

$$r = \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{\sqrt{[n(\Sigma x^2) - (\Sigma x)^2][n(\Sigma y^2) - (\Sigma y)^2]}}$$

where n is the number of data pairs.

Figure 39: Pearson product moment correlation coefficient (Bluman, 2011)

3.2.2. Study Area

All three streams examined in this study require an investment to remove excessive sediment, which prevents them from fulfilling uses designated through the Clean Water Act. Each drains an agriculture-dominated watershed, in different ecoregions of the state. Elm Creek in south-central Minnesota, the Buffalo River in western Minnesota, and the Whitewater River in southeastern Minnesota are impaired by their sediment loads.

3.2.2.1. Elm Creek

Elm Creek delivers water from 700 square kilometers (173,000 acres) of Martin and Jackson counties in south central Minnesota into the Blue Earth River, which drains into the Minnesota River then the Mississippi River. Elm Creek's watershed is dominated by row crop agriculture, with 86 percent of land producing corn and soybeans (Lenhart et al., 2010; MPCA, 2012b; Quade, 2000). Lenhart (2008) reviewed historic data to determine the stream had enlarged by as much as 250 percent in the headwaters, and had left behind several terraces as it adjusted to land use changes.

Prior to row crop agriculture, Elm Creek drained a prairie pothole watershed, with nearly 50 percent wetland coverage (Quade, 2000). European settlers began converting prairie and draining wetland to make way for farmland. In the early 1900s, public ditch systems were created to drain wetlands (MPCA, 2012b). In the past fifty years, planting of row crops has expanded significantly, and in the past thirty years, ditching and tiling efforts have intensified. Currently the Greater Blue Earth River Basin contains 5,446 kilometers (3,384 miles) of public drainage (ditch and tile) (MPCA, 2012b), and an unknown, but doubtlessly large mileage of private drainage, leaving wetland cover at under 2 percent (Quade, 2000) of Elm Creek's watershed. Coincidentally, precipitation has also increased across Minnesota in the past thirty years. Channel adjustments the creek made to prairie conversion were repeated as the intensity of land use and runoff volume increased.

As the stream adjusted, it incised a 0.002 to 0.0003 m/m channel through alluvial silt and clay loams of Des Moines Lobe till (Lenhart, 2008; Quade, 2000). Lenhart (2008) found the streambeds consist of silt to fine gravel. Quade (2000) estimates Elm Creek is eroding 272,155 to 362,874 kilograms per square kilometer (1.2 to 1.6 tons per acre) per year. The fine-texture of the channel and bed material allows the water to suspend upwards of 193 mg/L of sediment (Lenhart et al., 2011b). This value, and others like it, ranks Elm Creek as one of the highest contributors of sediment to the Blue Earth River, which is the largest contributor of sediment to the Minnesota River (Quade, 2000; Lenhart et al., 2011b), a river known for its muddy appearance.

Elm Creek is currently listed as impaired for fish bioassessments, turbidity (four reaches), *Escherichia coli*, and dissolved oxygen (MPCA, 2015a).

3.2.2.2. Buffalo River

The Buffalo River drains 3,100 square kilometers (768,000 acres) of Clay, Becker, Otter Tail and Wilkin counties of west central Minnesota into the Red River of the North, which continues through Canada's Lake Winnipeg and Nelson River on its way to Hudson Bay. The Buffalo River watershed is also predominantly agriculture, with 78 percent in production, 7 percent forested, 5 percent urban, 4 percent grassland, and 3 percent each open water and wetland (MPCA, 2014). Originally, the Buffalo River Watershed was a mix of forest, lake and prairie. Soils understandably range from gravel to silt and clay as the river moves from glacial moraines, and over ancient beach ridge on its way to the bed of Glacial Lake Agassiz (MPCA, 2012c).

Similar to other streams, the Buffalo River channel changed as settlers developed its watershed, and again as land use intensified (MPCA, 2014). At present, the Buffalo

River has adjusted to increased flow and sediment loading by growing generally more erosive, digging deeper, widening, and losing touch with its floodplain. The MPCA (2014) shows a list of negative aquatic habitat and water quality responses. For example, "Negative aquatic habitat response include direct loss of habitat by lack of pool scour, fine sediment accumulation in pools and the hyporheic zone, loss of hyporheic zone (region beneath and alongside a stream bed where mixing of ground and surface water occurs) productivity, loss of in-stream and overhead cover, substrate composition degradation, holding cover velocity, increase in temperature, lowered DO, macro macroinvertebrate impacts, loss of spawning gravels, loss of habitat diversity, loss of rearing habitat, lowered IBI scores, increased sediment supply, and accelerated bank erosion." Altered hydrology has been identified as "the single most important factor stressing the stream biology" within the Buffalo River (MPCA, 2014).

The Buffalo is currently listed as impaired for *Escherichia coli* (eight reaches), aquatic macroinvertebrate bioassessment (two reaches), fish bioassessment, turbidity (eight reaches), and dissolved oxygen (MPCA, 2015a).

3.2.2.3. Whitewater River

The Whitewater River drains 830 square kilometers (205,000 acres) of Olmstead, Winona and Wabasha counties on its way to the Mississippi River in southeastern Minnesota. The watershed is 66 percent agriculture (58 percent crops, 8 percent pasture), 14 percent wetland and wildlife management area, 13 percent woodland, and 7 percent other (MPCA, 2010). The headwater streams flow through gently rolling hills before cascading down limestone bluffs and ravines to a slough along the Mississippi. Originally this area's highly erodible loess soils were covered in prairies, oak savannah and hardwood forest (WRWP, 2016).

The Whitewater River channel has evolved with land use changes. Lands were cleared, and reaches were channelized for wheat farming in the 1850s (in 1868 the area became the nation's fourth largest wheat market), which switched to dairy and its supporting grasses and grains near 1900s (WRWP, 2016). Dairy remained dominant until relatively recently, when intensive row-crop agriculture took over (MPCA, 2010). Of the three subject watersheds, the Whitewater has the most perennial cover (wetland, WMA, woodland and pasture comprise 35 percent), but also the most relief change.

The river has a history of flooding and large aggradation events. For example, in the 1920s and 1930s, the river flooded 20 or more times per year, depositing as much as 4.6 meters (15 feet) of soil across the floodplain of the lower reaches (WRWP, 2016).

The Whitewater River is currently listed as impaired for turbidity (nine reaches) and nitrates (two reaches) (MPCA, 2015a).

3.3. Results

3.3.1. Lateral Erosion

Erosion rates ranged from 0.2 to 1.2 meters (0.6 to 4.1 feet) per year across the three rivers, with the Buffalo River coming in as the most erosive (highest maximum, average and median), and the Whitewater the least (lowest maximum, tied average and median). All were quite similar. For example, minimum erosion rates across the rivers were nearly identical, at 0.2 meters (0.6 or 0.7 feet) per year. Maximum erosion rates of 1.2 meters (4.0 and 4.1 feet) per year occurred on Elm Creek and Buffalo River, respectively. Average and medians were in the 0.5 to 0.6 meters (1.5 to 1.9 feet) per year range. The remainder of the results section will provide a summary of each variable, and how it relates to lateral erosion values.

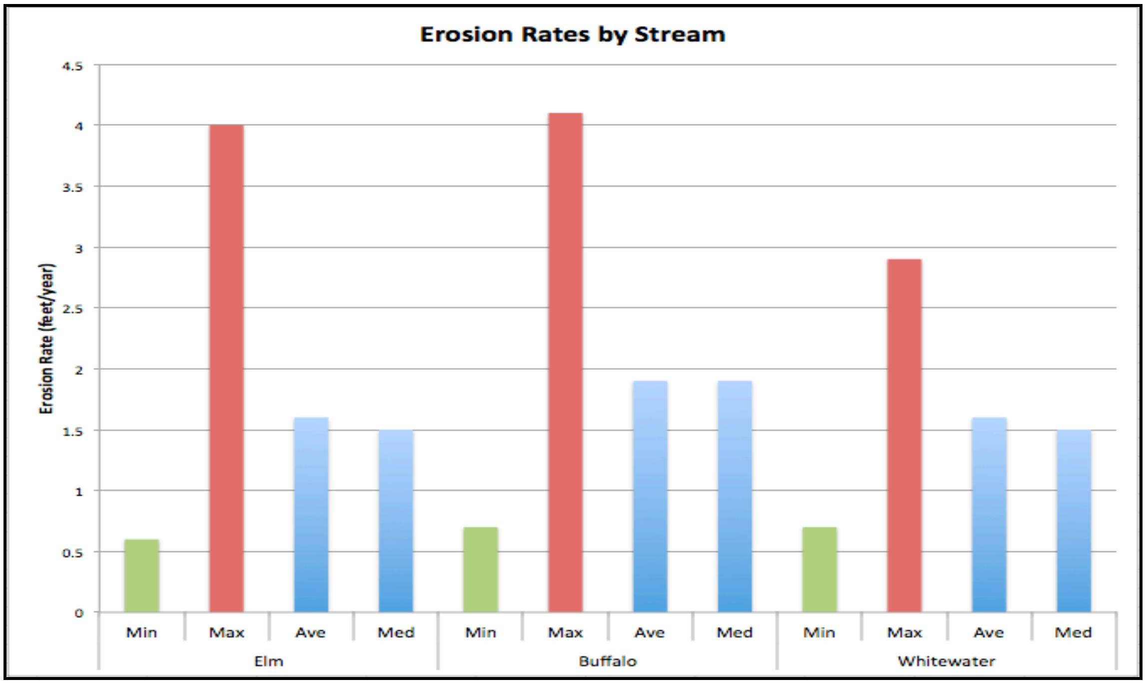

Figure 40: Erosion rates by stream

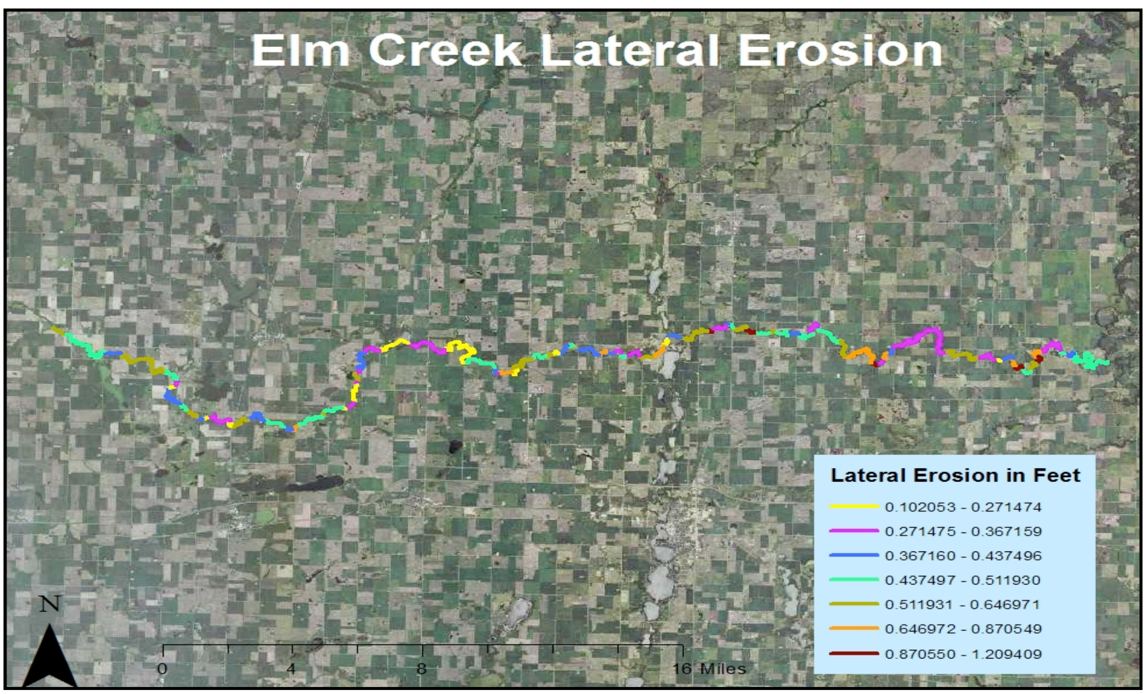

Figure 41: Elm Creek lateral erosion

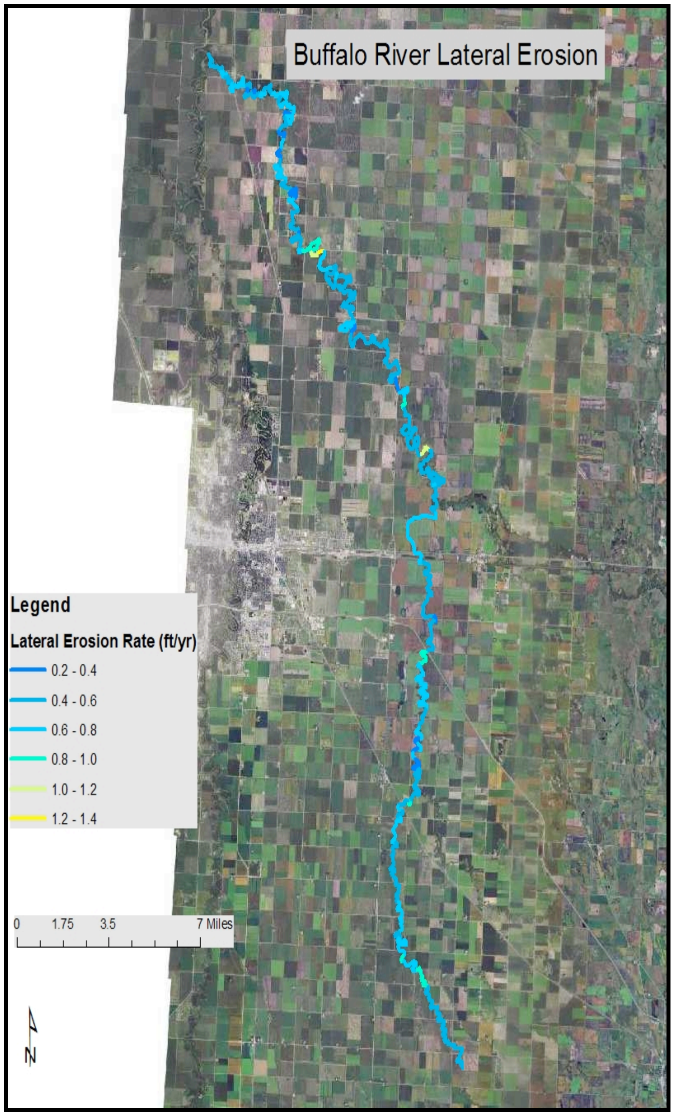

Figure 42: Buffalo River lateral erosion

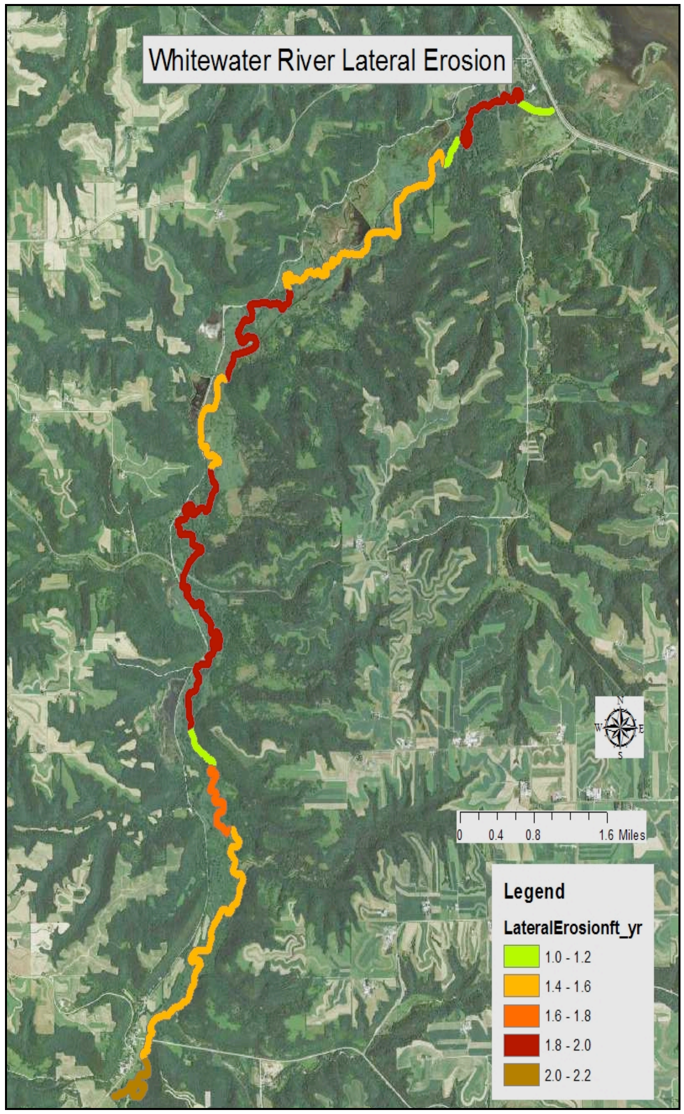

Figure 43: Whitewater River lateral erosion

3.3.2. Stream Mile (Size)

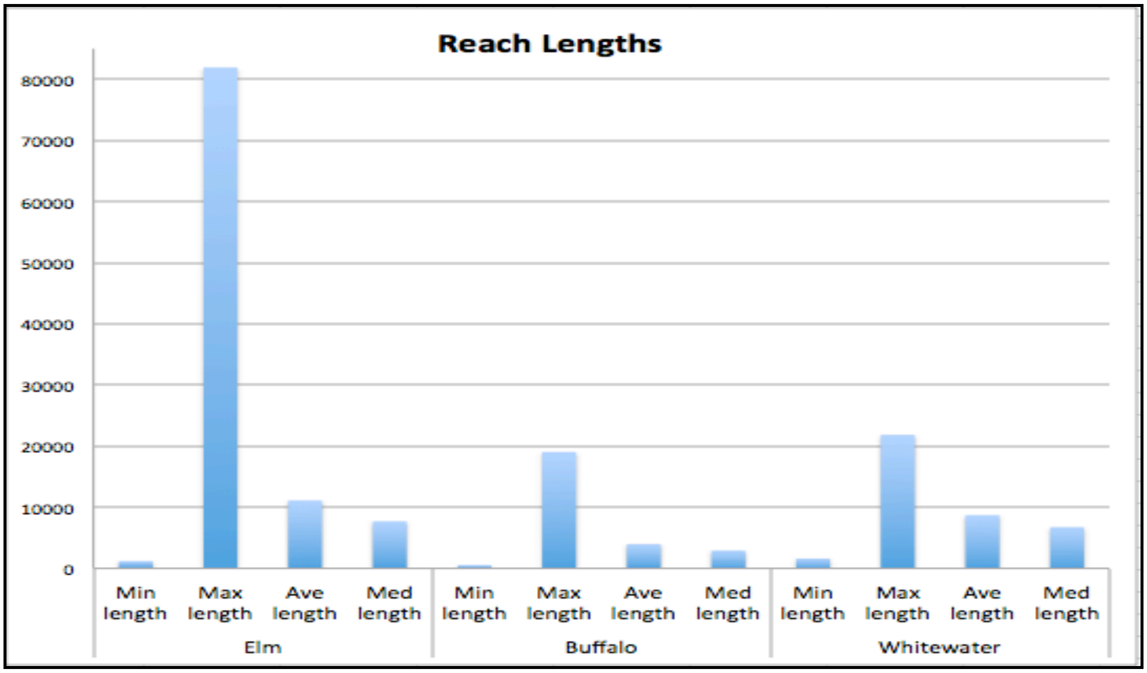

Figure 44: Reach sizes

Graphing erosion rates versus reach number allows a visualization of how erosion rates of the three streams look from headwaters (left side of the graphic, at reach number 0) to mouth (right extent of each stream's data). As seen above (Figure 44), the number and length of reaches is different from stream to stream. The graph (Figure 45), therefore, is for general trend observation, not a scaled comparison.

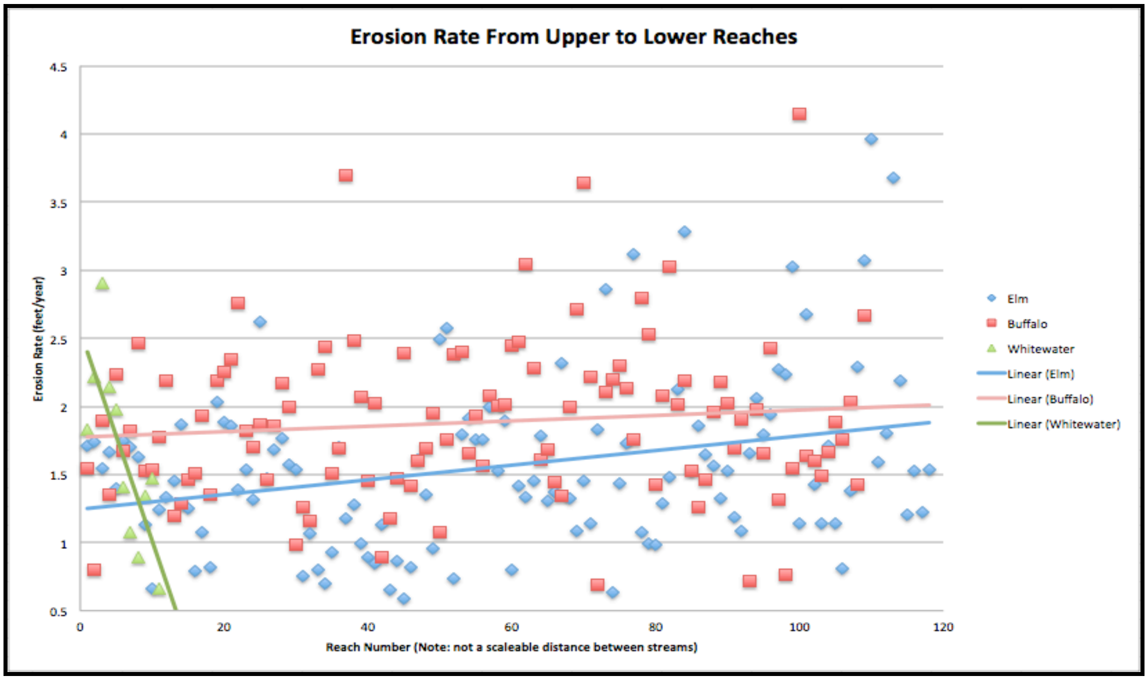

Figure 45: Erosion rate by reach number

3.3.3. Cover

As mentioned above, cover was numbered 1 through 4 from most herbaceous to most woody. Cover 1 was grass with less than 20% tree canopy, Cover 2 was grass with 20 to 40% tree canopy, Cover 3 was mixed with 40 to 80% tree canopy, and Cover 4 was forested with over 80% tree canopy.

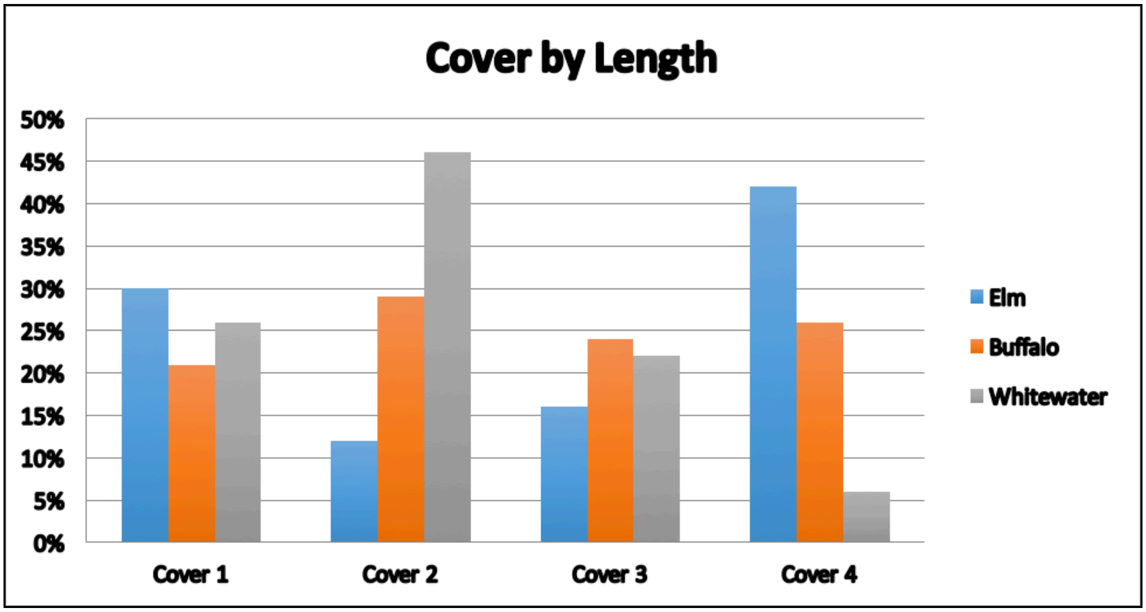

Figure 46: Cover by length of stream (feet of each cover divided total stream length)

The 172 kilometers (107 miles) of Elm Creek assessed was dominated by Cover 4 (42 percent), followed by Cover 1 (30 percent), Cover 3 (12 percent) and Cover 2 (12 percent). Most, 72 percent of the study section, was either under 80% aerial tree canopy (Cover 4), or grass with under 20% tree canopy (Cover 1).

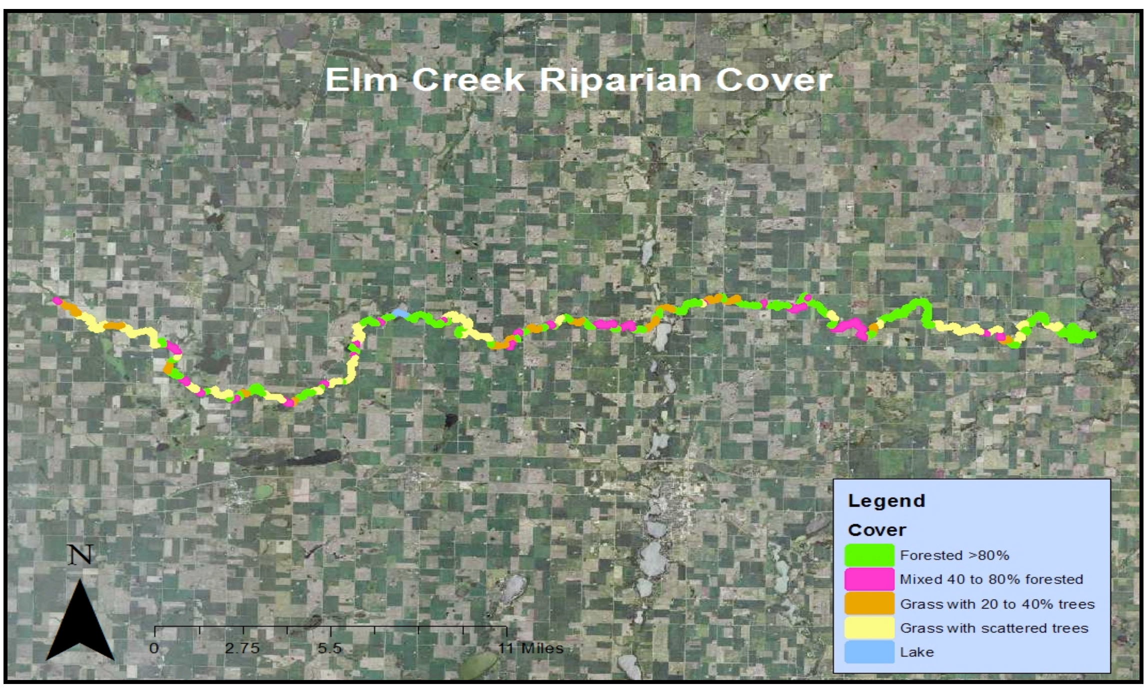

Figure 47: Elm Creek cover

Erosion rates in Cover 2 (grass with 20 to 40% tree cover) exceeded the whole-stream in terms of average, geomean, median, variance and standard deviation. Cover 1 (grass with under 20% tree canopy) erosion rate was also above the whole-stream median. Overall, however, erosion rates in covers 1, 3 and 4 were very similar on Elm Creek.

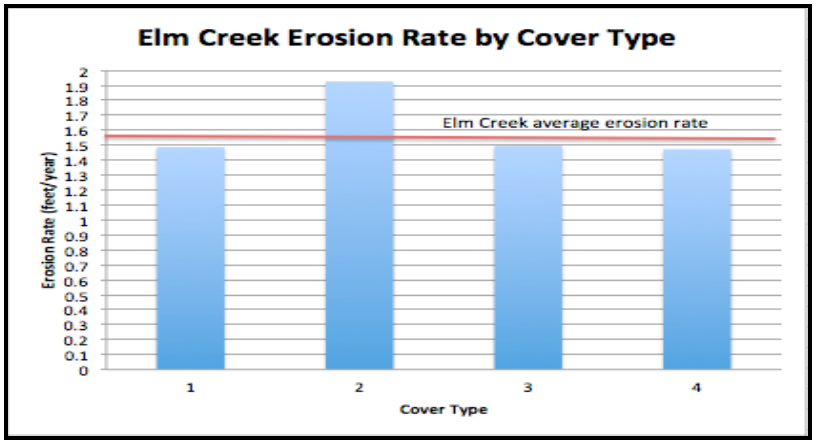

Figure 48: Elm Creek erosion by cover

Buffalo River cover types were much more evenly distributed, with Cover 2 at 29 percent, Cover 4 at 26 percent, Cover 3 at 24 percent and Cover 1 at 21 percent of the 132 kilometers (82 miles) assessed.

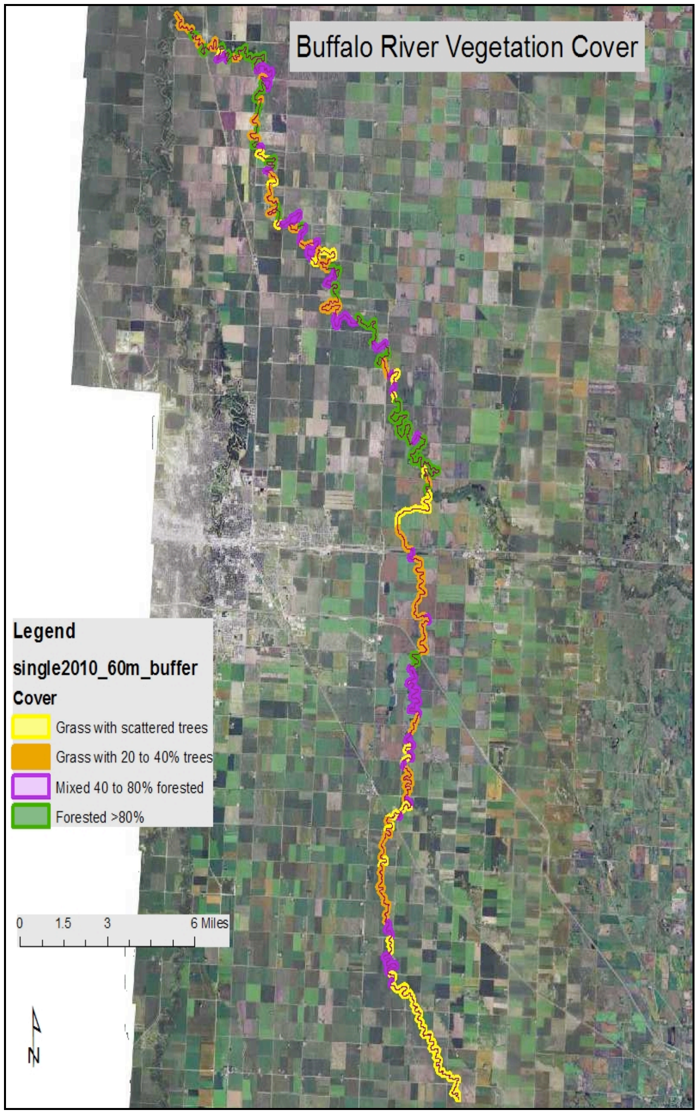

Figure 49: Buffalo River cover

Erosion rates in Cover 3 (mixed with 40 to 80% canopy) exceeded the whole-stream in terms of average, geomean, median, variance and standard deviation. The variance and standard deviation of Cover 2 and Cover 4 also exceeded the whole-stream values.

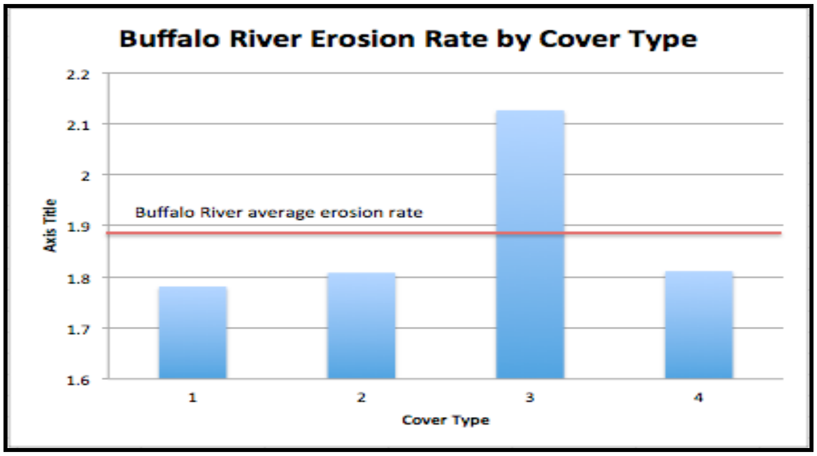

Figure 50: Buffalo River erosion by cover

Nearly half (46 percent) of the approximately 29 kilometers (18 miles) of Whitewater River assessed was Cover 2, 26 percent was Cover 1, 22 percent was Cover 3, and only a small fraction (5 percent) was Cover 4. Most, 72 percent of the study area, was under grass with under 40% tree canopy.

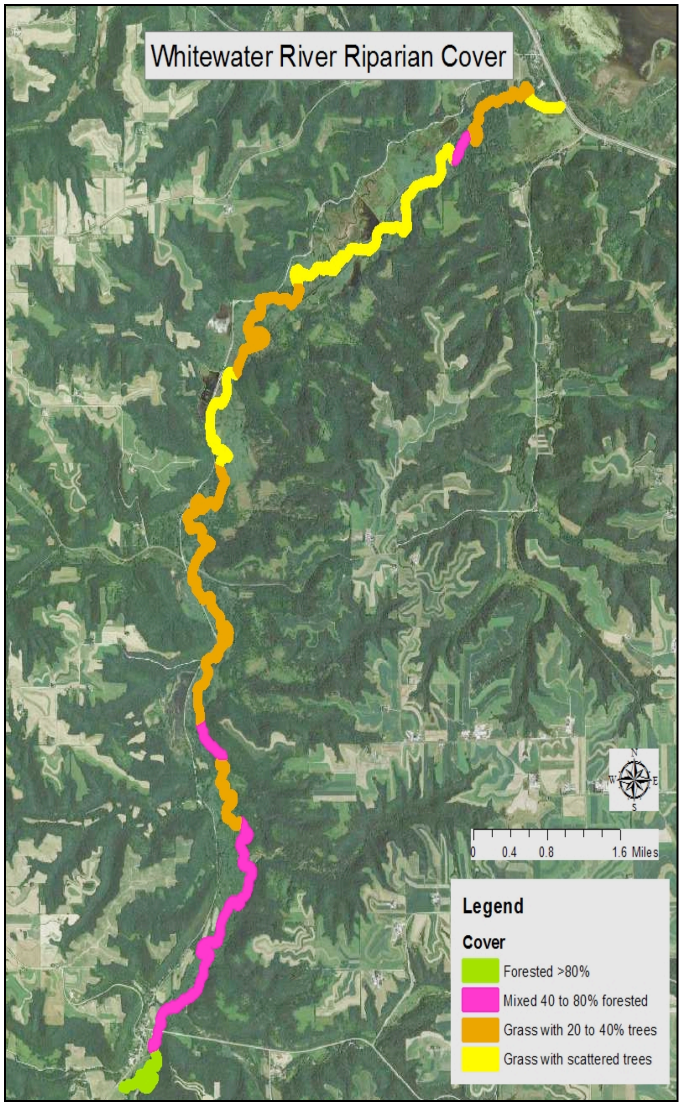

Figure 51: Whitewater River cover

Erosion rates in Cover 2 (grass with 20 to 40% tree cover) exceeded the whole-stream in terms of average, geomean, median, variance and standard deviation. Erosion rates in Cover 3 and Cover 4 were also above the whole-stream average and geomean.

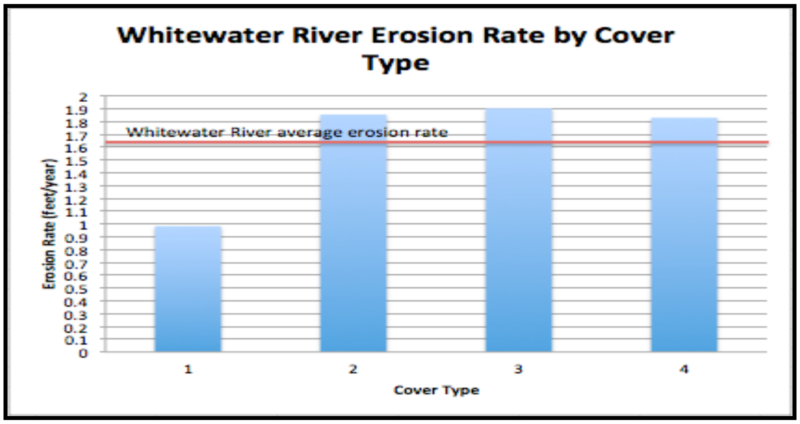

Figure 52: Whitewater River erosion by cover

3.3.4. Sinuosity

Reach sinuosity ranged from 1.0 to 12.9 for the three rivers. As described above, under 1.2, sinuosity is considered low, from 1.2 to 1.49 sinuosity is moderate, and above 1.5 sinuosity is high (Rosgen, 2008). Each stream was dominated by high sinuosity reaches (reaches with a length 1.5 or more than valley length), especially Buffalo River. Whitewater River had the longest reach and valley lengths, due to relatively homogenous vegetation cover.

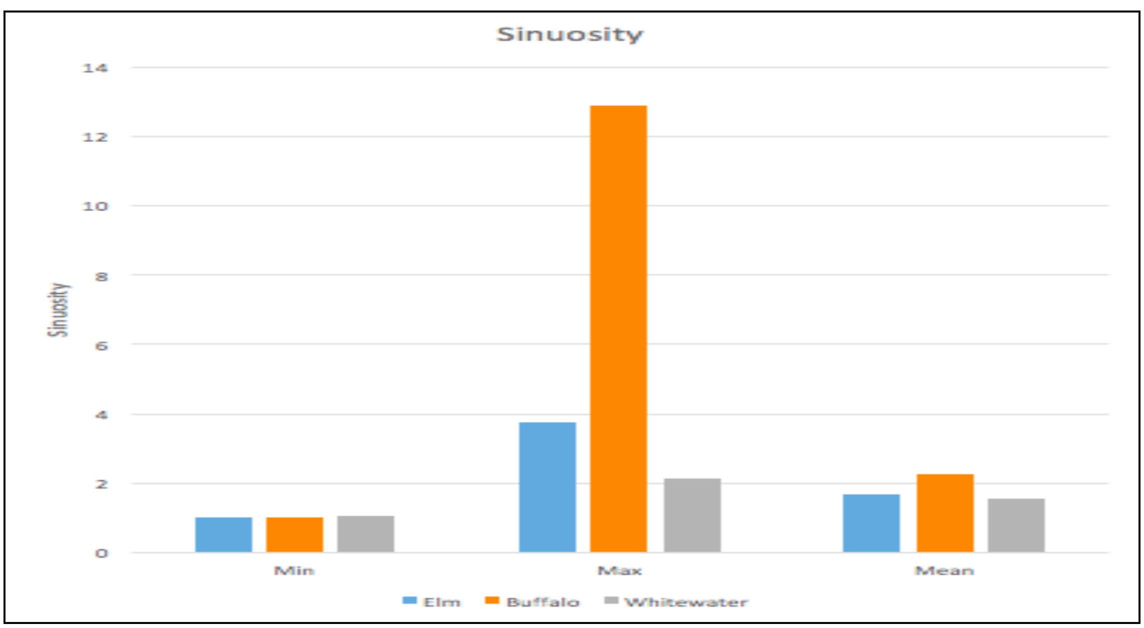

Figure 53: Sinuosity

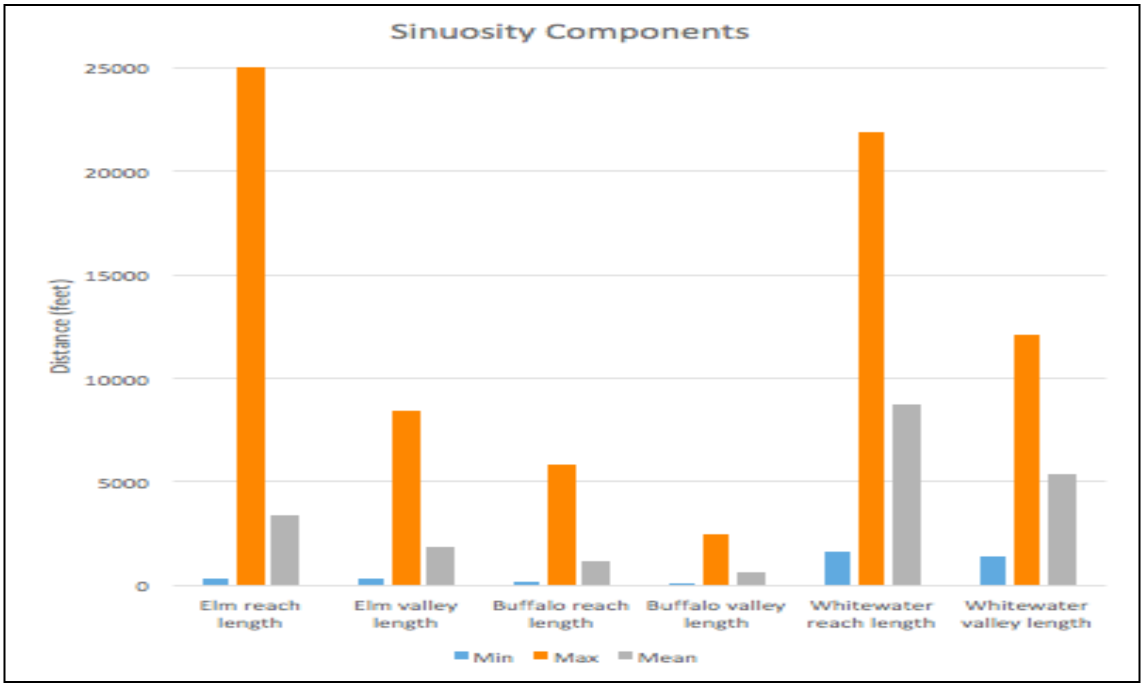

Figure 54: Reach length and valley length

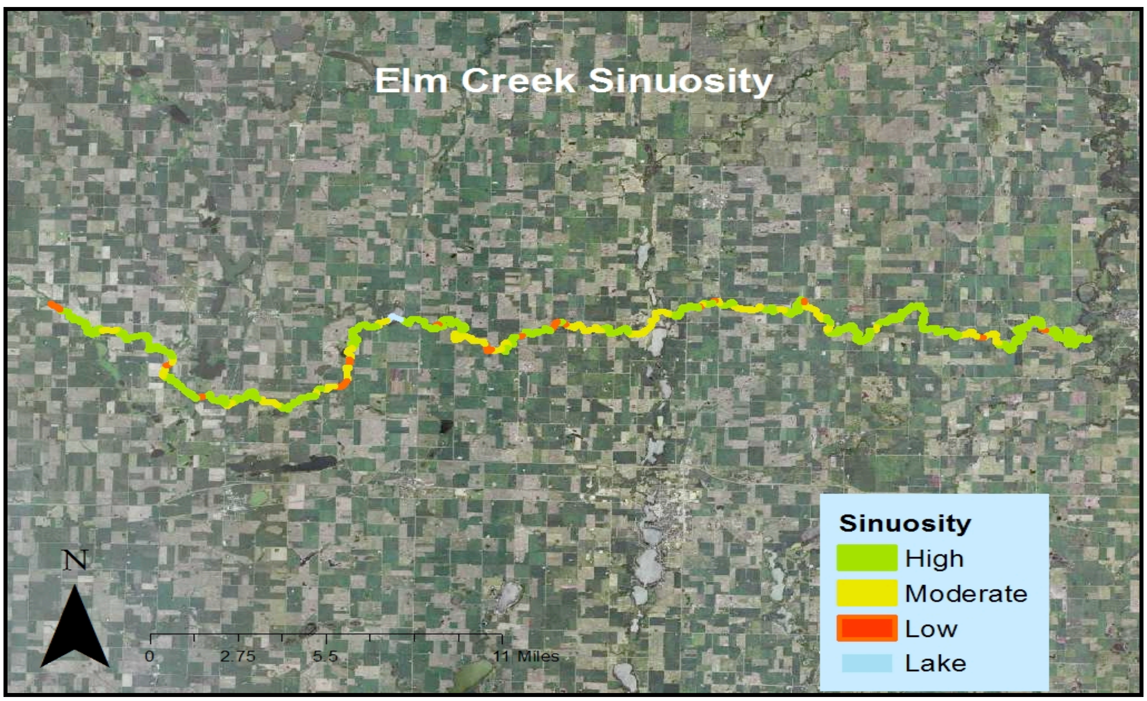

Figure 55: Elm Creek sinuosity

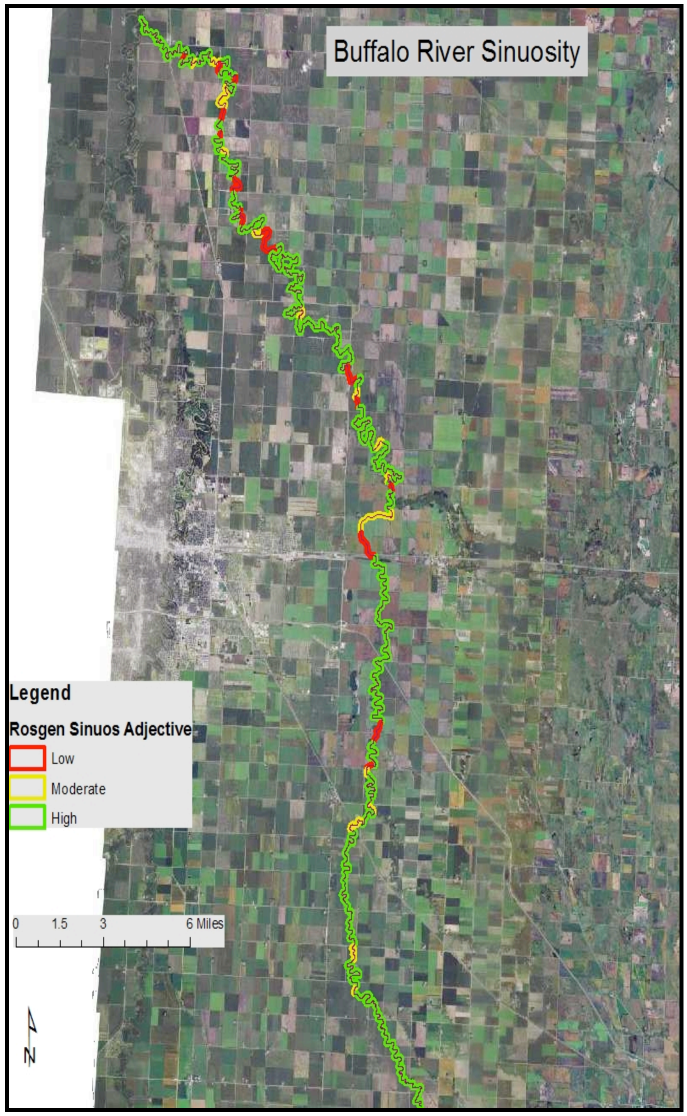

Figure 56: Buffalo River sinuosity

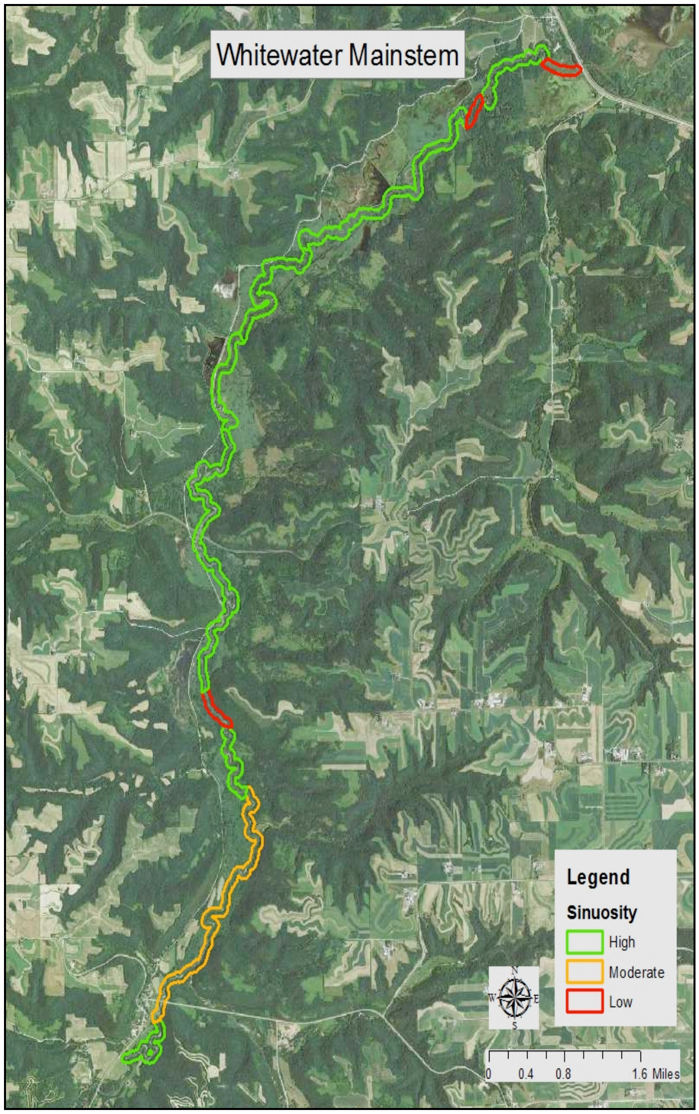

Figure 57: Whitewater River sinuosity

3.3.5. Near Bank Stress, Bankfull

The minimum near bank stress was 3 for all streams, but the maximum and average differed. Elm Creek had the highest near bank stress, with a maximum of 46 and average of 11. Buffalo River had the lowest near bank stress, with a maximum of 30 and average of 9. Whitewater River had slightly higher near banks stress values, with a maximum of 38 and average of 9. These values are all considered very low near bank stress, understandably, as measurement of sub-40 foot radii curves was prohibitive. As is, the measurements were designed to allow a comparison of reach-averaged near bank stress to reach-averaged erosion rates, and other variables.

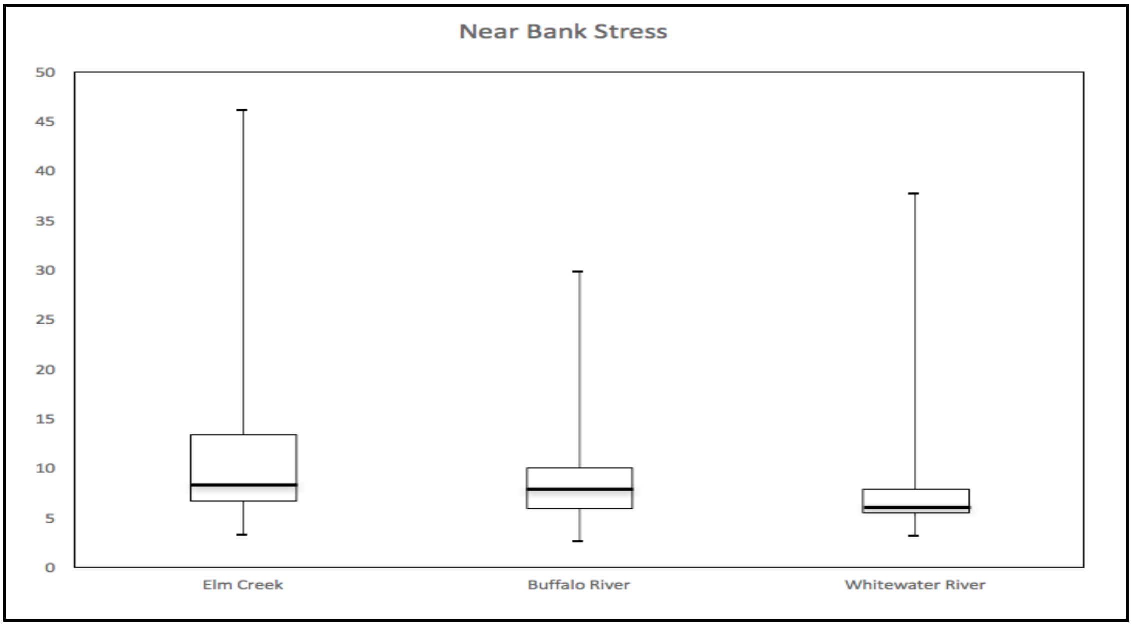

Figure 58: Near bank stress values are all very low. From top to bottom, these boxplot markers are the maximum, third quartile, mean, first quartile and minimum values.

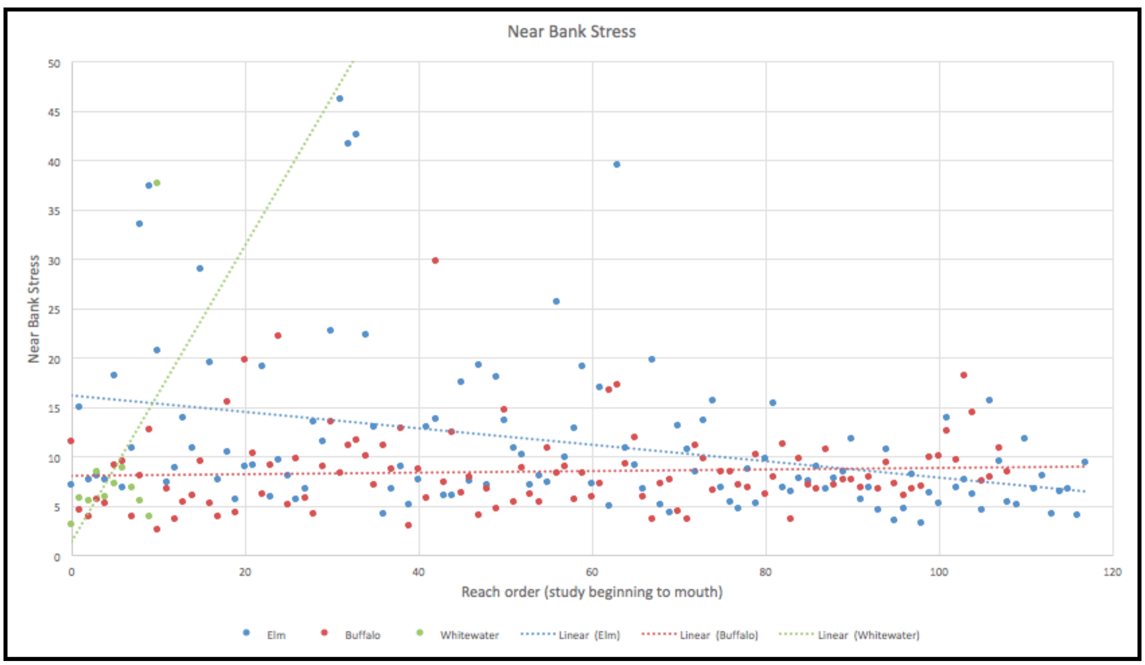

Figure 59: Near bank stress by reach number (not distance) from start of study area to mouth (left to right)

Elm Creek migrated 3 to 37 percent of its channel width per year, averaging 16 percent over the entire study area. Buffalo River migrated 3 to 34 percent of its channel width, averaging 10 percent. Whitewater River migrated 1 to 5 percent of its channel width per year, averaging 3 percent. Nearest the eroded distance to bankfull range in literature was Whitewater River's average, and the minimum values of Elm Creek and Buffalo River.

3.3.6. Elevations and Slopes of Water Surface and Banks

The water surface elevation pattern generally matched the high and low bank elevations. The surface of Elm Creek dropped 22 meters (72 feet) over the 172-kilometer (107-mile) study section. The Buffalo River dropped 6 meters (21 feet) over the 132-kilometer (82-mile) study section. The Whitewater River dropped 21 meters (68 feet) over the 29-kilometer (19-mile) study section.

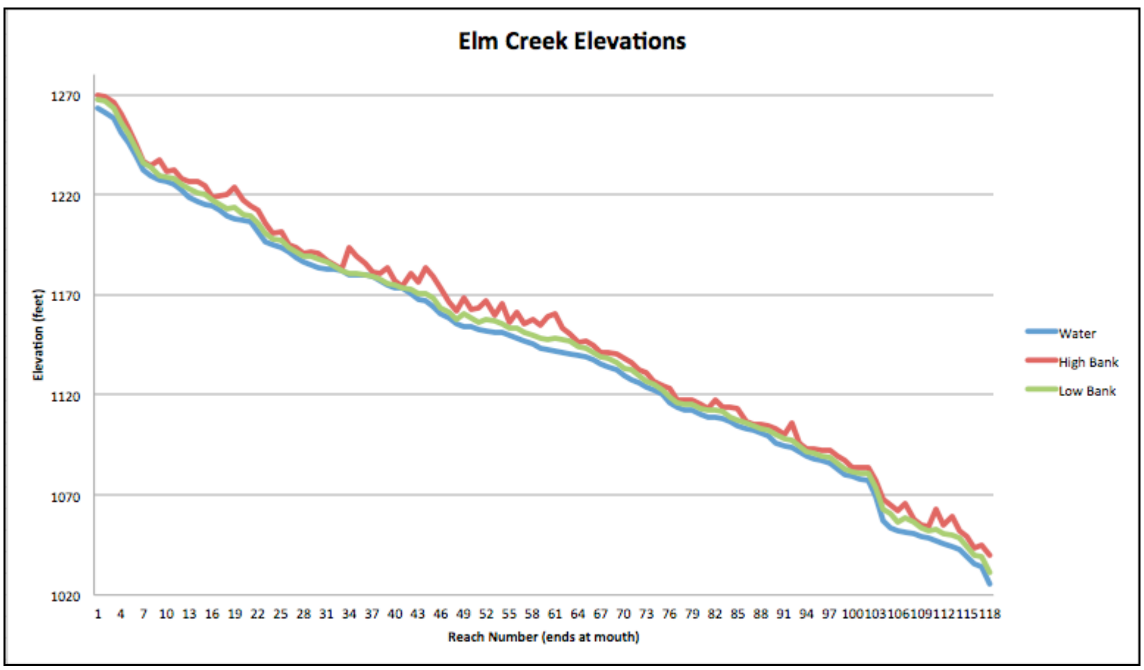

Figure 60: Elm Creek elevations, ending at mouth of stream

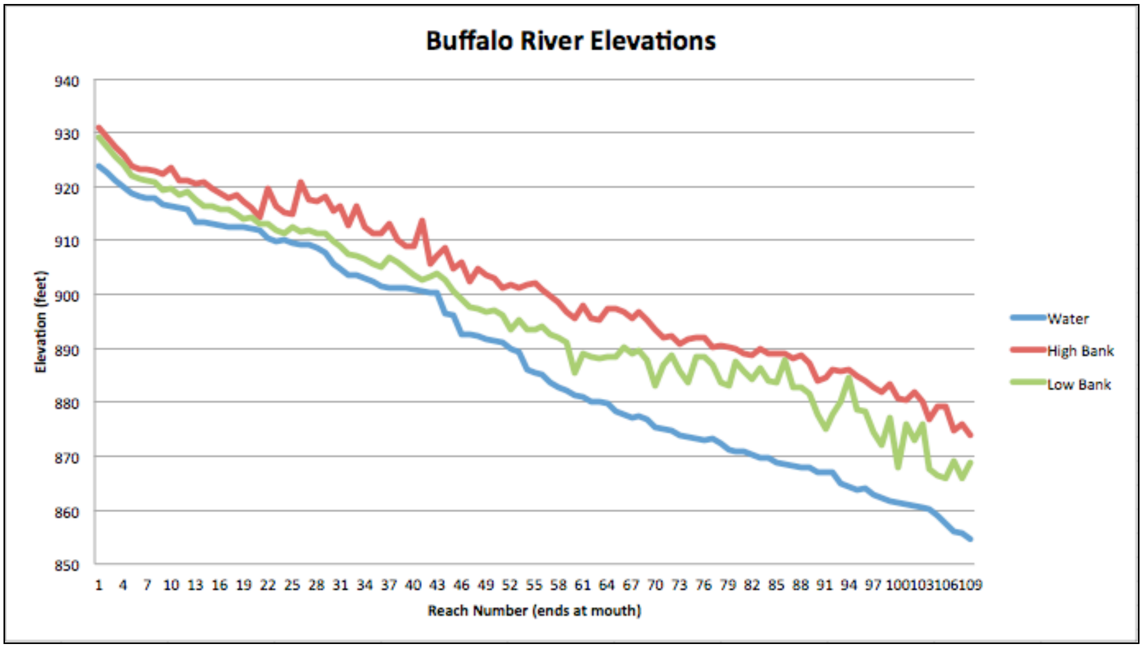

Figure 61: Buffalo River elevations, ending at mouth of stream

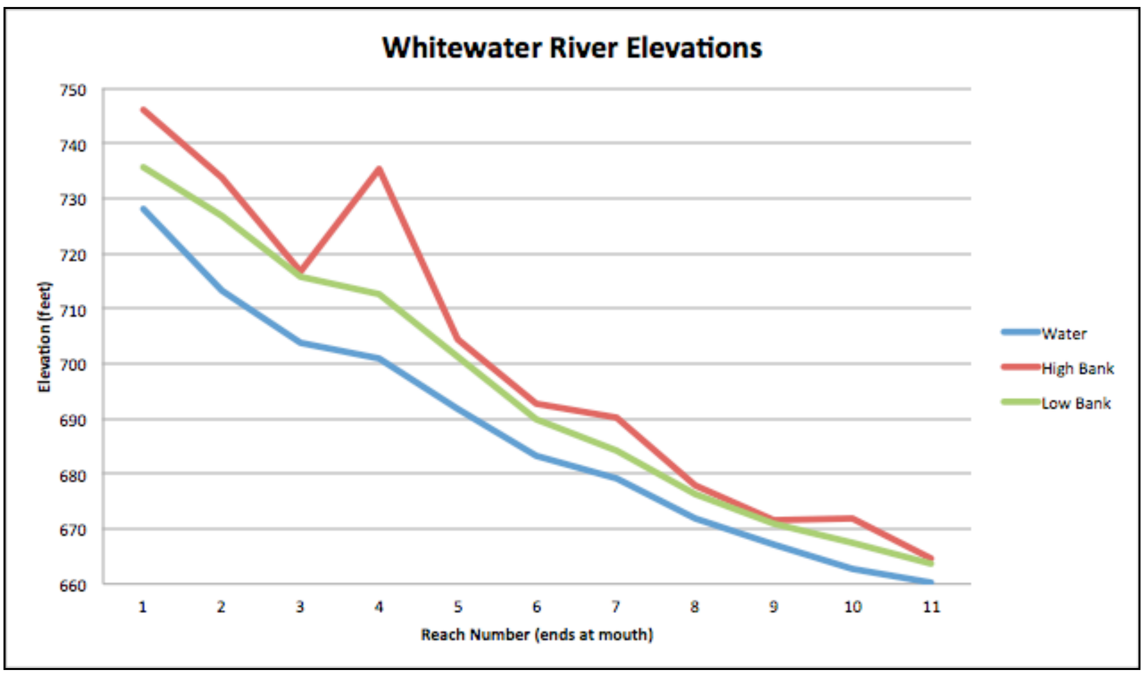

Figure 62: Whitewater River elevations, ending at mouth of stream

As seen in the relative elevation figures above, banks were generally highest in the center of the Elm Creek study area, mouth of the Buffalo River study area and beginning of the Whitewater study area.

Elm Creek had the lowest high banks (0.2 to 5.8 meters, or 0.8 to 18.9 feet), and low banks (0 to 2.3 meters, or 0 to 7.4 feet). Buffalo River had moderate high banks (0.7 to 6.6 meters, or 2.2 to 21.7 feet) and low banks (0.3 to 6.1 meters, or 1.1 to 20.0 feet). Whitewater had the highest high banks (1.3 to 10.4 meters, or 4.4 to 34.1 feet) and low banks (1.0 to 4.1 meters, or 3.3 to 13.6 feet).

Water and bank (measured parallel to the stream not perpendicularly) slopes were relatively constant along each of the study areas. The range of Buffalo River slopes narrows as the stream approaches its mouth.

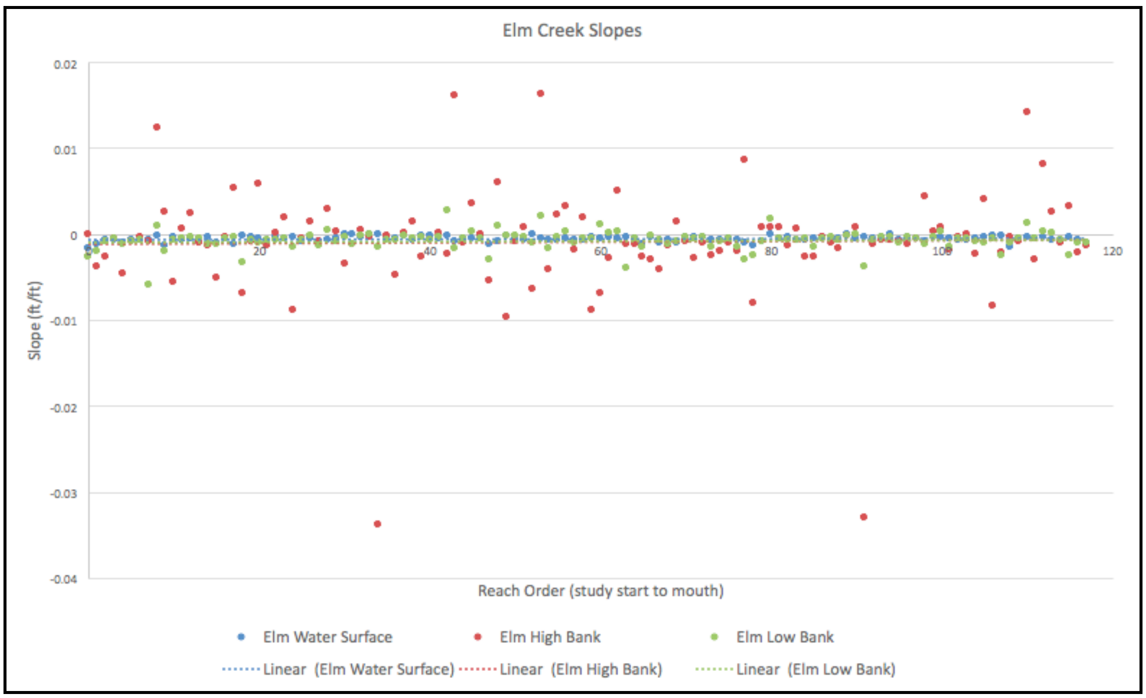

Figure 63: Elm Creek slopes, water surface and linear (bank-top) bank slopes

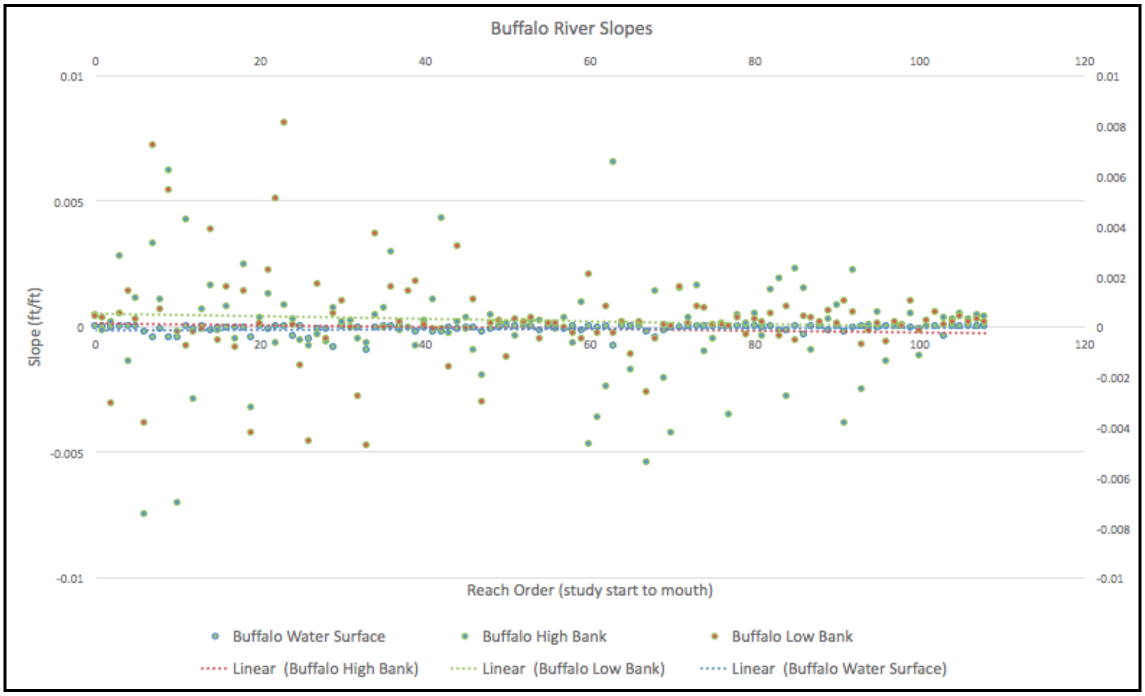

Figure 64: Buffalo River slopes, water surface and linear (bank-top) bank slopes

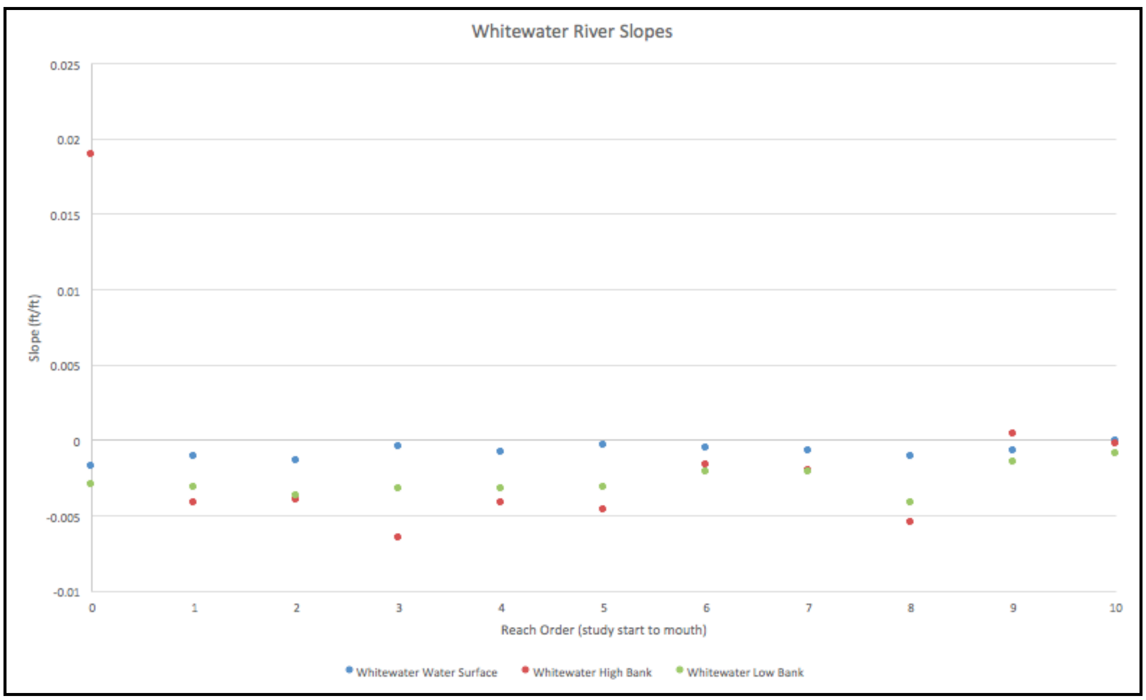

Figure 65: Whitewater River slopes, water surface and linear (bank-top) bank slopes

3.3.7. Correlations Between Measured Variables and Erosion

Elm Creek erosion rates were most related (with an absolute value ranging from 0.30 to 0.22) to low bank height, near bank stress, stream mile, low and high bank and water surface elevation, and radius of curvature, in descending order. Beyond that it was not correlated (under 0.2).

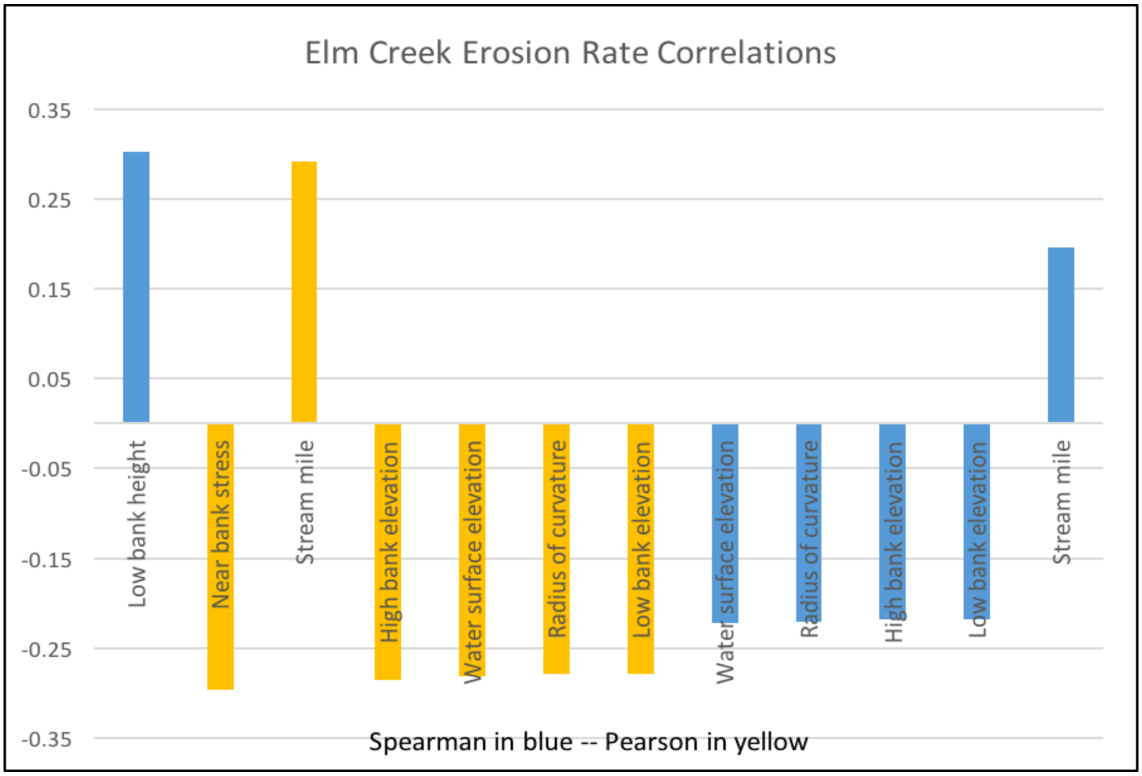

Figure 66: Elm Creek correlations

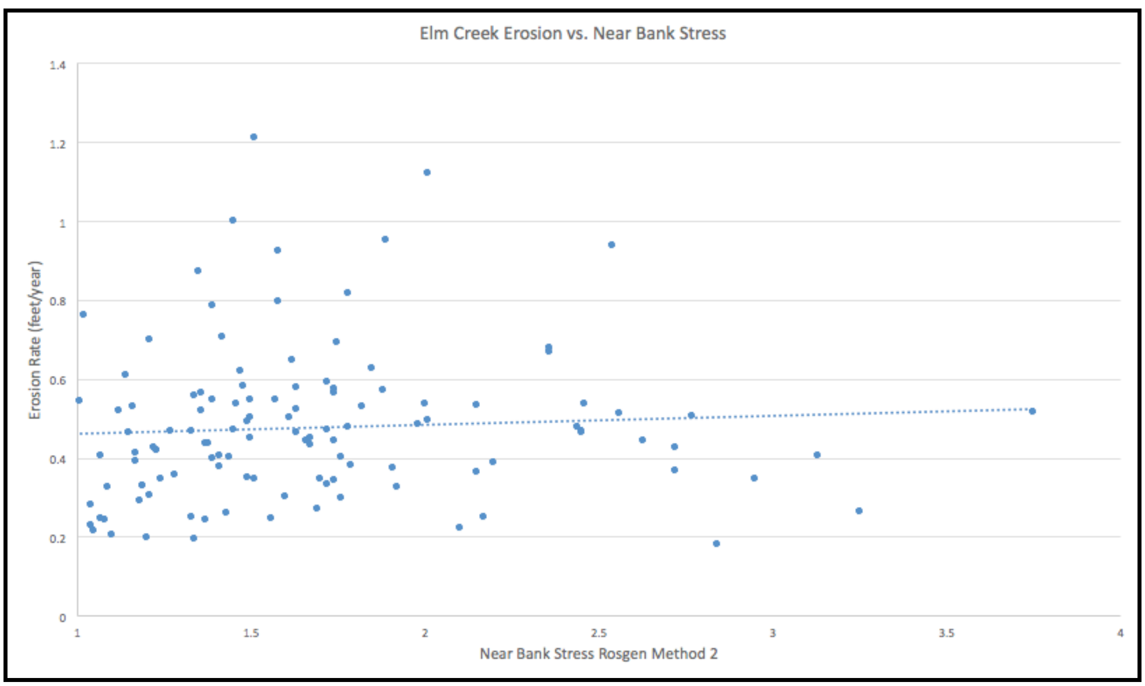

Figure 67: Elm Creek erosion rate versus near banks stress

The Buffalo River erosion rate was most tied to near bank stress (Pearson 0.34) and radius of curvature (Pearson 0.29). Every other variable is rated below 0.18.

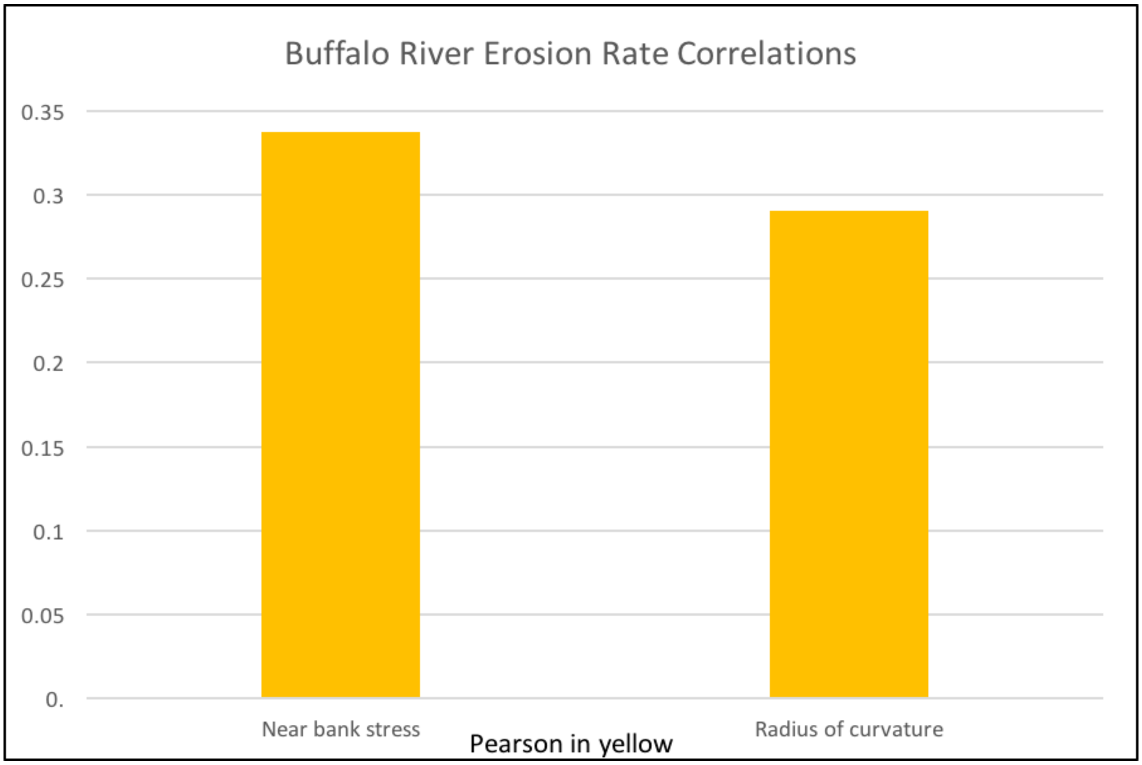

Figure 68: Buffalo River correlations

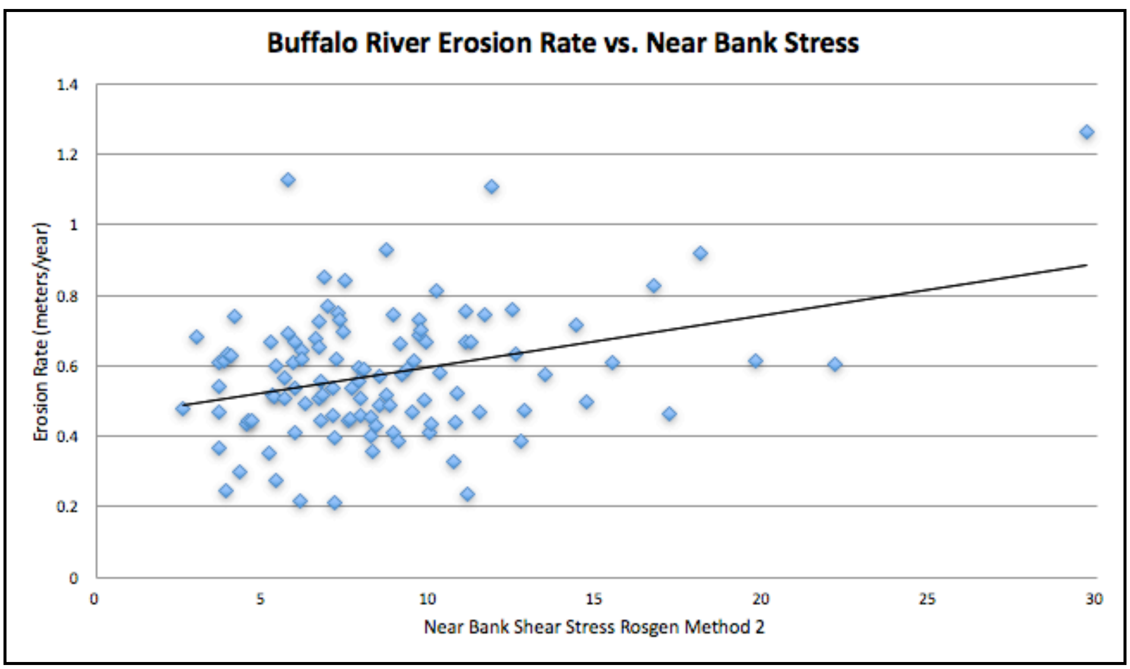

Figure 69: Buffalo River erosion rate versus near bank stress

The highest 18 Pearson and Spearman Rank correlations (with an absolute value ranging from 0.93 to 0.31) were on the Whitewater River. In composite, the correlations seem to explain what might be conceptually apparent in person: the bluff region of the study area is eroding faster than the bottomlands near the mouth. Erosion rates of the Whitewater are highest when high bank, low bank and water surface heights and elevations are highest; when stream mile is smallest; where cover is mostly trees (the bottomlands has scattered trees and meadow wetland); and where radius of curvature is highest (sinuosity increases – radius of curvature decreases – after the river drops through the bluffs).

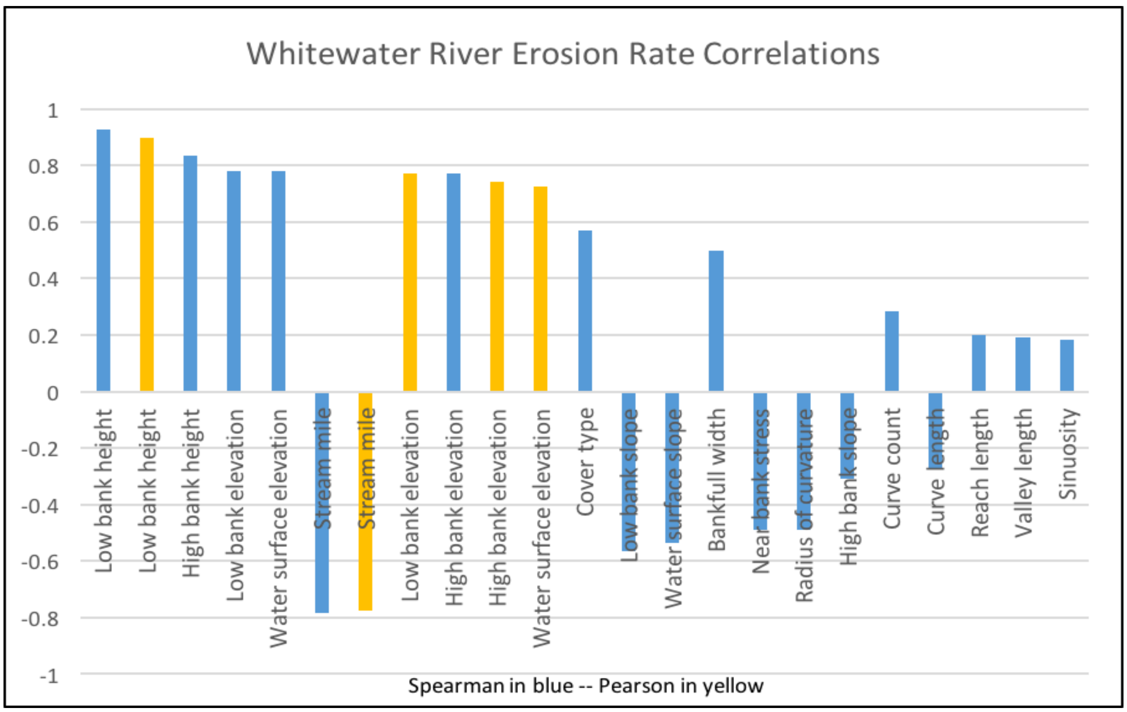

Figure 70: Whitewater River correlations

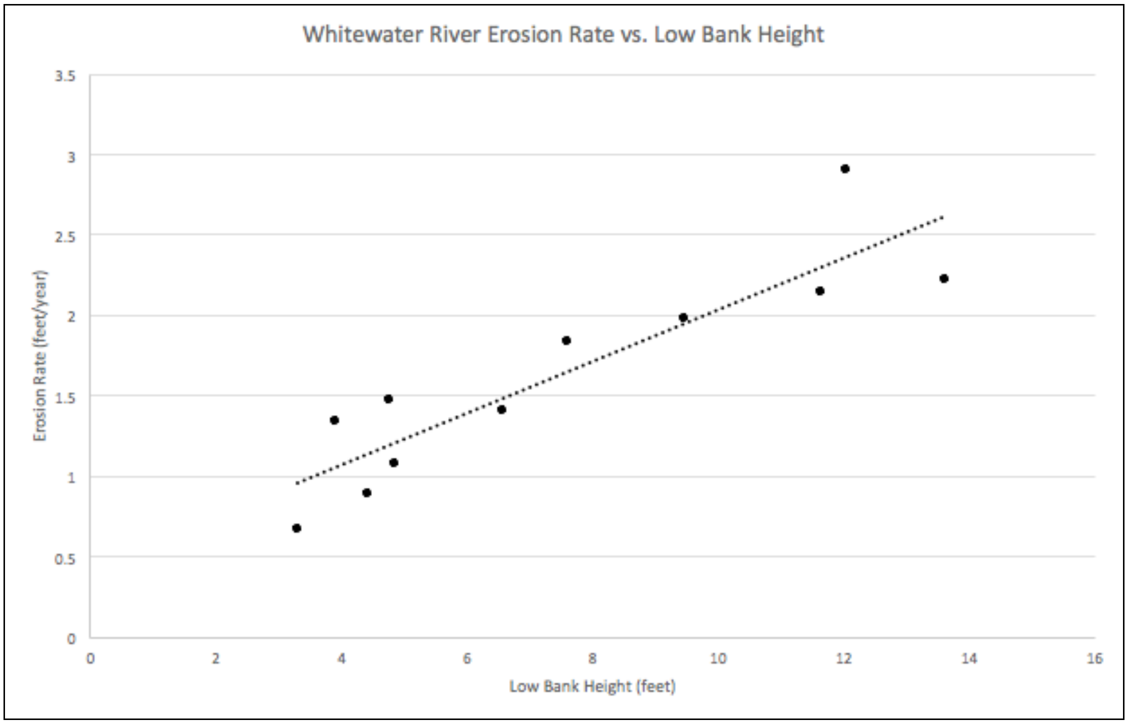

Figure 71: Whitewater River erosion rate versus low bank height

3.4. Discussion

This study quantified GIS-measurable stream attributes, and compared them with erosion rates of three agriculture-dominated streams. Of special significance was whether herbaceous or woody species dominated reaches had measurably less erosion. Knowing what to plant along an erosion-prone bank, or knowing where to focus planting or other erosion control methods will save time and effort in minimizing unwanted soil loss.

GIS tools designed by ESRI and Ellefson for ESRI's ArcMap were used to measure variables potentially associated with lateral erosion. This study ultimately compared lateral erosion with stream mile, cover, sinuosity (as well as reach length, valley length), near bank stress (as well as radius of curvature, bankfull), curve count, curve length, bank height (high and low), bank elevation (high and low), bank slope (high and low), water elevation, and water slope.

3.4.1. Cover Type

Cover was of special interest, given the desire of resource managers to recommend the best vegetation for erosion suppression. Vegetation type was not well correlated with erosion rate in this study. This is not surprising, given the complexity of vegetation's role in stream stability.

Many other studies have noted vegetation can play a major role in the form and erodibility of a channel (Gran and Paola, 2001; Hopkinson and Wynn, 2009).
Some considerations of vegetation type and erosion rate include: high stem density can lower erosion rates (Gran and Paola, 2001); herbaceous vegetation may provide superior freeze-thaw protection in winter, whereas forests may dominate the remainder of the year (Wynn and Mostaghimi, 2006b); trees may remove more moisture from the banks through evapotranspiration, increasing stability, whereas grasses may produce more mechanical support (Simon and Collison, 2002); herbaceous reaches may encourage more deposition (Trimble, 1997; Allmendinger, 2005); streams may widen as forests establish in response to increased channel roughness, but narrow again as the system matures (McBride, et. al., 2007); herbaceous reaches may best stabilize small streams in smaller floods, whereas forested reaches may best stabilize large streams in larger floods (Hawkins et al., 1997; Griffin and Smith, 2004; Vincent et al., 2009; Collier and Quinn, 2003; Camporeale, 2013; Rood et al., 2014); rooting depth, density and size vary widely by soils, groundwater depth, species and testing method (Simon and Collison, 2002; Wynn et al., 2004); large woody debris in a stream can accelerate erosion (Shankman,

1993) or protect its banks (Rood et al., 2014); and the choice between woody and herbaceous species as the best bank stabilizer in small streams may not apply to large streams.

The type of vegetation growing along stream banks may be chosen in large part by the stream itself (Shankman, 1993; Camporeale et al., 2013). Camporeale et al. (2013) sampled 31 significant studies of fluvial influences on vegetation distribution, and explains three common lateral distributions, each with a limiting factor. In the first, maximum biomass is present at the bank and decreases with distance from the channel. This occurs when depth to water is the limiting factor on growth. Biomass patterns are reversed in the second pattern, increasing in size with distance. This occurs when flooding is the limiting growth factor. In the third, a combination of water table, sedimentation and flooding produces a more uniform growth pattern, with nearby vegetation limited by flooding and distant vegetation limited by a declining water table. Vertical distributions are also common, with streams moving seeds, mineral and organic sediment, water, chemicals and nutrients along a channel and outward during floods (Camporeale et al., 2013).

An on-site investigation of the three study watersheds by Underhill (2013) cataloged dominant species by strata (Table 6). These data showed a predominance of shallow-rooting reed canary grass (*Phalaris arundinacea*) at each sample site. Regardless of cover category, this aggressive, non-native species may skew rooting depths across the watersheds (Braun, 2016).

Table 7: Cover species (Braun, 2016)

Parameters		Buffalo River	Elm Creek	Whitewater River
Count of Sampling Sites by Dominant Strata	**Herbaceous**	5	6	6
	Shrub	3	2	3
	Forest	2	2	1
Dominant Vegetation by Strata		Herbaceous • Reed Canary Grass (*Phalaris arundinacea*) Shrub • Red-osier Dogwood (*Cornus sericea*) • Sandbar Willow (*Salix interior*) • Nannyberry (*Viburnum lentago*) Forest • Green Ash (*Fraxinus pennsylvanica*) • Boxelder (*Acer negundo*)	Herbaceous • Reed Canary Grass (*Phalaris arundinacea*) • Tall Coneflower (*Rudbeckia lacinata*) • Field Horsetail (*Equisetum arvense*) Shrub • Red-osier Dogwood (*Cornus sericea*) Forest • Boxelder (*Acer negundo*) • Black Willow (*Salix nigra*)	Herbaceous • Reed Canary Grass (*Phalaris arundinacea*) Shrub • Honeysuckle (*Diervilla sp.*) • Nannyberry (*Viburnum lentago*) • Common Elderberry (*Sambucus canadensis*) Forest • Boxelder (*Acer negundo*)

3.4.2. Stream Mile (Size)

Erosion rate was relatively well correlated with stream mile and its associated elevations. Elm Creek erosion rates increased as the stream dropped in elevation, and increased in size. Lenhart et al. (2010) found turbidity and total suspended solids – both related to soil presence in the water column – increased exponentially from headwaters to the mouth of Elm Creek. These studies apparently support each other by finding bank erosion, turbidity and total suspended sediment loading increase along the length of Elm Creek.

Nanson and Hickin (1986) found stream size can explain up to 70 percent of mean bank erosion and channel erosion. Preliminary analysis of DNR Whitewater erosion data also points to stream size as a dominant variable (Ellefson, 2016). Conversely, Underhill (2013) found no significant erosion difference between the upper, middle and lower reaches of the same three stream systems when erosion rates were measured using BEHI.

The Whitewater River expressed the most erosion in the upper portion of the study area. This high correlation between low stream mileage, higher elevations and higher erosion rates is perhaps explained by the dominance of erodible bluffs in the upper reaches, and the dominance of flatter floodplains in the lower reaches.

3.4.3. Near Bank Stress

This study showed near bank stress and its numerator, radius of curvature, were correlated to lateral erosion in all three stream systems. Interestingly, the pattern of correlation differed.

Elm Creek and Whitewater River exhibited higher erosion in areas of lower near bank stress and lower radius of curvature (the numerator of near bank stress) values. Again, the NBS rating table inverts values (see Table 5), so the erosion rates are highest when the radius of curvature is lowest (tightest curves), and near bank stress rating is lowest (extreme). Buffalo River erosion rates are highest when the radius of curvature is highest (widest curves), and near bank stress rating is lowest (very low). Low erosion rates in areas of tight curves (low near bank stress rating) may be due to curvature-induced secondary circulation, which limits bank erosion by limiting velocity and bed shear stress (Blanckaert, 2009).

Interestingly, bankfull width (the denominator of near bank stress) was not well correlated with lateral erosion rates. USDOT (2012) noted bank stability was especially dependent upon the variability of channel width. Gran and Paola (2001) found a relationship between vegetation density and channel width, and noted a number of studies with similar results (Hadley, 1961; Brice, 1964; Zimmerman et al., 1967; Charton, 1978; Graf, 1978; Andrews, 1984; Hey and Thorne, 1986; Huang and Nanson, 1997; Rowntree and Dollar, 1999). Schottler et al. (2013) suggested the strong relationship between flow and channel width could explain channel widening as a dominant means of streams adjusting to increased flow (versus slope and depth).

3.4.4. Low Bank Height

Of all the variables considered, erosion rates along Elm Creek and Whitewater River were most correlated with low bank height. The higher the minimum bank height, the higher the erosion rate. The lowest banks may allow dense vegetation to grow to the water's edge (USDOT, 2012).

Abernathy and Rutherfurd (1998) found short banks were most susceptible to windthrow (erosion associated with trees falling into streams) because the short distance between the top of bank and groundwater severely limited rooting depth, whereas a 60 centimeter (24 inch) tall bank allowed tree roots to stretch enough to resist windthrow and protect the bank from erosion. Interestingly, the maximum bank height was not as well correlated to erosion rates.

Bank height can be a sign of an unstable channel. Thorne (1991) states there is a critical bank height at which a stream changes from incising to rapid widening. Widening has been noted in the study streams (Lenhart, 2008; MPCA, 2014).

3.4.5. Limitations and Future Studies

This study is limited and benefited by scale. GIS allows a user to review erosion rates, and compare those rates to other stream characteristics on the watershed scale. Unfortunately, measurements needing a closer view are inaccessible. Furthermore, by viewing the system from the watershed scale, some variables measurable by GIS are recorded discretely and averaged over a reach (such as near bank stress and erosion rate); whereas other variables are naturally measured once over a reach (such as sinuosity and slope). Variables measured discretely and averaged may benefit from more measurements per reach.

For example, a finer measurement of radius of curvature, for a more refined measurement of near bank stress may also prove useful. Due to the size of the study areas, the lower limit of radius of curvature measurements was set at approximately 12 meters (40 feet). An exhaustive catalog of radii may show a stronger or weaker correlation between erosion rates, radius of curvature and near bank stress.

Wetland presence was recorded but later disregarded. As mentioned above, the NWI did not seem accurate. Additionally, wetlands visible through aerial interpretation corresponded too frequently with ditched portions of the streams, which may have further skewed the relationship between wetlands and lateral erosion.

Additionally, stream power is often cited as a variable in erosion rates. The time commitment required to prepare a DEM for stream power calculations prevented its inclusion in this study. It may, however, prove to be a valuable variable to compare these erosion rate data against.

An important consideration in any study of erosion variables is the maturity of the stream. This study did not determine if the lateral erosion measured was a channel widening response from past land-use or channel disturbances.

Finally, using the exiting data, a multivariate analysis, to determine the relationships among the variables would be enlightening. Additionally, Cover 2 and Cover 3 data could be removed for a second look at whether erosion rate has a relationship with a more definite herbaceous versus forested reaches. Breaking the streams into smaller sections, or increasing the n value, and rerunning the project could alter the results.

3.5. Conclusion

There was no clear correlation between erosion rate and vegetation type in this study. Underhill's (2013) review of the same streams did not find a correlation between cover type and erosion rates either, but did find the rooting characteristics of grass may be the best erosion control in small reaches, shrub rooting characteristics in medium reaches, and tree rooting characteristics in large reaches.

The most influential erosion control may be on tight bends with high banks towards the mouth of Elm Creek, wide meanders on the Buffalo River, and tight bends with high banks towards the beginning of the Whitewater main stem. Given the mouth of the Elm and beginning of the Whitewater mainstem are larger stream reaches, the tight bends with high banks here may benefit most from tree cover.

Chapter 4: Setting Priorities in Erosion Control: Values, Policies and Targeted Restoration

4.1. Introduction

In a state renowned for its "sky blue waters," with parks, trails and cities focused around its nearly 12,000 lakes and 148,000 kilometers (92,000 miles) of streams, clean water is big business in Minnesota. Examples of the value of Minnesota's clean water and bank stability include recreation spending, water industry earnings, property values, and structure stability. The cost of preventing degradation of clean water, through policies requiring responsible land-use, can be significantly cheaper than the cost of cleaning water and restoring eroding banks. Effective erosion control policy is essential to Minnesota's water economy, as is restoration. Restoration can be expensive. Implementation of bank stabilization, and channel restorations must be carefully designed to provide the largest benefit to the resource. Understanding, preventing and mitigating the causes of water quality impairments, such as turbidity from excessive erosion, is imperative to so many aspects of life and recreation in Minnesota.

Minnesota's $13 billion a year tourism industry is actively engaged in clean water, understanding the link between its own success and water quality (Spencer, 2015). Fishing alone generates between $2.5 billion and $2.4 trillion annually (Hult, 2015; ASA, 2013; Kelly, 2012, AP, 2013). Excluding fishing, hunting and wildlife viewing, Minnesota's outdoor recreation (canoeing, camping, hiking, etc.) generates $11.6 billion in consumer spending and $3.4 billion in wages in Minnesota annually (OIA, 2012).

Tourism, fishing and outdoor recreation aside, employees of Minnesota's water industry earned over $885 million in wages, and exported over $870 million in water technology in 2014 (EQB and DEED, 2015). Many millions of dollars more are spent on water research, water services and water restoration annually in the state (EQB and DEED, 2015). The quality of Minnesota's water resources is a significant economic driver.

Studies around the country have found a significant relationship between the clarity of water and property values. Krysel et al. (2003) reviewed the relationship between water clarity and property values in northern Minnesota. The group found a 1-meter (3.3-foot) change in water clarity altered property value by several dollars to nearly $2,000 per meter ($600 per foot) of shoreland frontage (1996-2001 dollars). In summary, the value of properties in northern Minnesota, across a lake could change from $30,467 to $150,560,122 (1996-2001 dollars).

The economics of most issues can be broken into prevention versus treatment: in this case, erosion control versus stream restoration. Minnesota currently has a network of buffer regulations designed to keep more-erosive land use practices from diminishing water quality. State-wide, as part of the shoreland rules, Minnesota counties and cities govern the activities allowed in "shoreland impact zones," a buffer of land between the shore and a setback within which impervious surfaces, vegetation clearing, and other activities are more limited (MN Rules 6120.3300). Lake Improvement Districts allow localized control (MN Rules 6115.0900). Ditch authorities require perennial vegetation for 5 meters (1 rod, or 16.5 feet) on either side of county ditches (MN Statutes 103E.021).

Minnesota recently passed a buffer law, inspired by a water quality report by the Minnesota Pollution Control Agency (2015b). The report found that watersheds dominated by agriculture were often impaired by phosphorus, nitrogen, suspended solids and bacteria; all pollutants that could be decreased through distancing land uses from open water. The law was designed to improve water quality through a uniform buffer requirement (Laws of Minnesota 2016, Chapter 85 (S.F. 2503)). The law requires a perennial 15-meter (50-foot) average buffer on public waters. If at 9 meters (30 feet) of buffer is unreasonable, the landowner may substitute an approved water quality practice.

The cost of preventing erosion is difficult to estimate, as it can range from voluntarily allowing sensitive areas to exist in a natural state to passing regulations outlining acceptable water-friendly uses. On the low end, there may be no cost. On the high end are rare attempts to quantify the economics of land stewardship.

East of Minnesota, Wisconsin passed a statewide shoreland zoning standard in 2011, modifying allowable development within 305 meters (1000 feet) of waterbodies. The Department of Natural Resources was tasked with weighing the costs of implementing the rule with the benefits to the economy. It found four quantifiable variables: increased property values from phosphorus reduction ($29,871,401), improved recreational opportunities from phosphorus reduction ($399,598), cost of mitigation to property owners ($21,678,742), and county implementation costs ($1,207,140). The balance tipped in favor of the zoning standards, with property value increases and enhanced recreation coming in $7.4 million ahead of the cost of lost use and implementation. These figures are summed over the first ten years of the new rules. After this point, the enhanced benefits continue indefinitely, but the costs drop to pre-implementation rates. (WiDNR, 2012).

South of Minnesota, Iowa farmers could save $104 per hectare ($42 per acre) in water treatment by implementing erosion control practices (Iowa Learning Farms, 2013).

At approximately $1 billion annually, this could underestimate the value of erosion control to society by 20 to 90 percent, by leaving out services such as water retention and cleaning drinking water (Eller, 2014).

As seen in the Wisconsin example, prevention can be beneficial compared to no action. It can also be less expensive than restoration. After generations in the channel modification business, Congress required the U.S. Army Corps of Engineers to catalog erosion of the nation's navigable waters. In 1969, the Corps identified over 805,000 kilometers (500,000 miles) of banks damaged by sloughing, degradation, or head-cutting (USACE, 1981). The damages were estimated at $591.1 million (2016 dollars), with repairs at $2.8 billion (2016 dollars) (USACE, 1981).

The most recent comprehensive review of national or regional data on stream restoration costs available considering literature and various agencies is from the now-defunct National River Restoration Science Synthesis database. Both Bernhardt et al. (2005) and Palmer and Allan (2006) analyzed these 1990-2003 data, now 14-27 years old. Bernhardt et al. (2005) found the total of regional projects recording federal expenditures (excluding local matches) at $7.5 billion. Extrapolating this estimate nationally, and noting the number would likely be an underestimate, Bernhardt et al. (2005) found the United States spent over $1 billion a year from 1990-2003 (not adjusted for inflation). In the past two decades, interest in and implementation of stream restoration projects has increased exponentially.

Local estimates are difficult to come by as well. Recently in Minnesota (July 2014 to June 2016), channel improvement projects large enough to require an environmental impact study screening by Environmental Quality Board, totaled over 68.6

kilometers (42 miles) (six additional projects had unknown linear distance) (EQB Monitor, 2016; DNR, 2013a; DNR, 2013b; MCWD, 2013; Scott County, 2013; Martin County, 2014; MCWD, 2016; TRPD, 2016). The Minnesota Department of Natural Resources implemented 86 additional (not overlapping EQB projects) stream habitat improvement projects from 1994 to 2015 (21 years), with 28 percent categorized as channel restorations, 30 percent as dam removals, and 42 percent as modifications (DNR, 2016c). Of these 86 projects, 41 dam and culvert replacement projects (generally with rock ramps and better culverts, respectively) were implemented to reconnect stream reaches while improving fish passage, habitat, and human safety. The investment of the 37 reporting financial data, was over $12.9 million, mostly from 2000-2008 (DNR, 2010).

Water quality restoration is also expensive. In 2014, Minnesota paid approximately $125 million to clean lakes, streams and groundwater in agriculture-dominated watersheds of excessive nutrients and bacteria (Marcotty and Kennedy, 2015). In 2015, the state's department of health drinking water budget was $17.8 million, with a goal of ensuring 97 percent of the state's population has access to water meeting state quality standards (MDH, 2015). In 2016, Governor Dayton and Lieutenant Governor Smith proposed to invest $220 million in land use and infrastructure improvements tailored for clean water (MN, 2016). Over the 20 years beginning in 2011, the U.S. Environmental Protection Agency estimated Minnesota would need $1.4 billion in drinking water treatment, which totals $7.4 billion after considering distribution, source, storage and other costs (USEPA, 2013). This number increased to $11 billion in recent years (MN, 2016). According to the U.S. Environmental Protection Agency, cleaning contaminated drinking water costs 10 to 30 times as much as prevention (MDH, 2015).

4.2. Priority Setting in Watershed Restoration Research

4.2.1. Overview

Cost estimates are essential in the development of management and restoration plans, grant applications and the Total Maximum Daily Load process. Stretching a limited budget to maximize erosion control requires a targeted approach. Local government units and other land-use organizations routinely address turbidity impairments with the help of erosion estimating and restoration prioritization tools.

The University of Minnesota partnered with the Minnesota Department of Agriculture, with funding through the Minnesota Clean Water, Land and Legacy Amendment, to quantify the rates and drivers of channel erosion; to develop an empirically based erosion index for the Upper Midwest; and to identify a means of prioritizing erosion reduction, thereby reducing sediment and phosphorus loading. Using empirical methods to estimate erosion rates allows land managers to rapidly identify areas in need of conservation measures, without using more time-intensive modeling. By tailoring existing empirical methods to local streams, the erosion rate index will more accurately estimate bank loss of similar regional systems. This will allow Minnesota land managers to maximize the effectiveness of restoration programs.

Workshops held with local government unit staff and landowners highlighted a need for less-complicated erosion quantification tools, and a desire for stream stabilization to be located within the channel (UMN, 2015). Attendees observed that an increasing number of erosion control grants and the TMDL process require use of an official quantification tool, which are not always practical to apply (UMN, 2015).

Given the grant was provided by the Minnesota Department of Agriculture, the University of Minnesota chose three agriculture-dominated watersheds in three different ecoregions: Elm Creek in the Western Corn Belt Plains of south central Minnesota, with flat to gently rolling heavy silt to clay loams (UMN, 2015); Buffalo River in the lakebed clays of former Glacial Lake Agassiz, its outer relict beach ridge, and Central Hardwood Forest of northwestern Minnesota (UMN, 2015); and Whitewater River in the Driftless Area of southeastern Minnesota, which begins as a flat plateau, but drains through bluffs.

As mentioned above, the first goal was to measure long-term erosion rates and investigate erosion drivers. To measure Elm Creek, Buffalo River and Whitewater River erosion rates via GIS, a two centerlines were digitized per river. The years 1991 and 2010 were digitized and compared for Elm Creek and Buffalo River. Due to issues with imagery, the years 203 and 2010 were digitized and compared for Whitewater River. The centerlines were buffered to incorporate banks, and cut into reaches at vegetation breaks. Elm Creek and Buffalo River had over 100 reaches each, whereas Whitewater had significantly fewer vegetation changes. Two GIS erosion rate measurement tools were used and compared: DNR Static Lateral Migration Tool (Ellefson, 2015), and BBE Dynamic Lateral Migration Tool (Titov, 2015a). After the attribute tables were populated with erosion rates, additional GIS-measurable variables were added per reach, such as sinuosity, near bank stress, and vegetation cover.

Triplett (2014) assessed the balance between deposition and erosion with turf mat squares; cataloged the particle size and deposition rate; collected species, age and location for vegetation patterns; and analyzed timing, magnitude and duration of base and peak flows. These data showed pointbar deposition of approximately 3,538,000 kilograms (3,900 tons) per year. The increased discharge submerged deposition locations for more of the growing season, thereby decreasing vegetation establishment, and subsequently decreasing deposition. This behavior may be contributing to the increased erosion, and widening observed in the streams in this study.

Underhill (2013) extracted roots to measures root depth and root density throughout the soil profile across the three river systems. He also recorded vegetation cover, soils, and erosion predictions via BEHI. The study found no correlation between root density and BANCS erodibility factors, noting other factors may play a role.

Riparian monitoring well networks recorded groundwater elevations fluctuating by upwards of 2 meters (6.6 feet) along Elm Creek and the Buffalo River, but staying 1 to 3 meters (3.3 to 9.8 feet) below the surface (UMN, 2015). These monitoring data indicated groundwater seepage was not a significant factor in bank erosion at these sites, in fact on several occasions the banks absorbed higher streamflows, due to the depth of groundwater in the bank profile (UMN, 2015). Additionally, motion-activated and time-lapse cameras were mounted along Elm Creek to visually document erosion events, (UMN, 2015).

The geochemical sampling and SWAT modeling separated the volume contributions from tile drains, overland flow and groundwater to characterize source waters. During unfrozen periods of the year, tile drainage was the source of 58 to 90 percent of Elm Creek's water. Whitewater River was a combination of surface and low-residence groundwater, with little tile contribution. (UMN, 2015)

The second goal was to develop regional bank erosion prediction graphs for Minnesota. Sass and Keane (2012) found modifying the BEHI section of the BANCS model allowed better erosion prediction outside of Colorado, where it was originally developed. However, this method did not yield a strong correlation between BANCS erosion rates and field measured erosion rates in Minnesota. However, substituting erosion rates taken from aerial photography allowed the creation of more appropriate, regional prediction graphs (MDA, 2015).

The third goal was to assist in prioritizing restoration sites. Presnail (2013) developed a Stream Restoration Prioritization Score Sheet and associated guidance manual to walk users through 13 metrics found most helpful in determining the erosion rate, need for protection, and ease and cost of restoration. This tool built on several existing tools, and was presented as an option to local government staff.

4.2.2. Discussion

4.2.2.1. Erosion Measurement

This study compared several means of quantifying erosion: GIS (DNR Static Lateral Migration Tool by Ellefson (2015); BBE Dynamic Lateral Migration Tool by Titov (2015a) and BANCS (Rosgen, 2008). Other methods used to measure these streams included BSTEM, bank pins and cross-section surveys. Each has advantages and disadvantages.

Considering the alternative, the time commitment needed to calculate erosion rates on 333 kilometers (207 miles) of three streams, as well as measure or catalog 19 potential erosion variables via GIS was reasonable. GIS methods allow measurement of stream channel shifts over great temporal and spatial scales. Nineteen years of migration across an entire watershed can be measured, without visiting a statistically significant number of sites annually.

While the time savings is significant, there are some variables that are much more accurately measured on site. With knowledge of the landscape, some species may be cataloged from aerial photography, and therefore rooting depth might be inferred, but more precise cover, species composition and rooting characteristics should be done on site. On site erosion measurements or estimates allow (or require) collection of information such as bank height, angle, material and layers; root depth and density; channel dimensions; and cover.

For watershed-scale erosion calculations, and coarse-scale hotspot identification and variable identification, GIS is a reasonable choice. For regional erosion estimates, with on-site variable measurements, and TMDL-ready results, the modified BANCS model is a reasonable choice.

4.2.2.2. Erosion Stabilization

Analysis of rooting characteristics, cover composition and erosion rates of Elm Creek, Buffalo River and Whitewater River point towards no discernable difference between herbaceous-dominated and woody-dominated erosion rates (this research; Underhill, 2013; Braun, 2016). The domination of reed canary grass (*Phalaris arundinacea*) at 22 of 30 sample sites does call into question the instances of low root depth and density (UMN, 2015; Braun, 2016).

Reed canary grass is an aggressive, non-native species, with a dense and shallow root system, often stopping short of 0.3 meters (1 foot) (Mueller, 1941; Klimesova and

Srutek, 1995). It is present throughout the state of Minnesota, commonly forming monocultures in disturbed, and wet environments, such as wetlands and riparian zones.

In aggregate, the UMN (2015) study points towards control of invasive reed canary grass, especially on banks 2 to 3 meters (6.6 to 9.8 feet) high, as a means of increasing rooting depth, and bank stability. Granted, the grass is quite aggressive, and large-scale control may be extremely difficult in many areas.

Near bank stress, radius of curvature, stream size, and low bank height showed some correlation to erosion rates. Focusing efforts on increasing rooting depth in areas most linked to erosion could optimize stabilization efforts. For example, where Elm Creek and Whitewater River have higher near bank stress, tighter radii of curvature, larger stream volumes, and higher minimum bank heights, they also have higher erosion rates. Where Buffalo River has lower near bank stress, and wider radii of curvature, it has higher erosion rates. These areas could be targeted to maximize productivity.

Hundreds of other studies have examined various aspects of lateral erosion (Kummu et al., 2008), many of which explored the best cover for erosion control. While debate continues as to whether tree, herbaceous or shrub species or a combination is best for stream bank stability, buffers are valuable.

4.3. Summary

There is value in vegetated buffers along streams, regardless of the vegetation strata. A buffer as narrow as 1.5 meters (5 feet) can remove the majority of total suspended solids, and a large fraction of nutrients (UMN, 2011). Compilations of buffer studies found a 1.5-meter (5-foot) buffer could remove 65 percent of total suspended solids, 31 percent of total phosphorus, and 19 percent of total nitrogen (UMN, 2011); and a 15-meter (50-foot) buffer could remove 85 percent of total suspended solids, 68 percent of phosphorus, and 66 percent of nitrogen (UMN, 2011), or higher: 97 percent, 91 percent, and 94 percent of the same (Lee et al., 2003). Burkart et al. (2004) reviewed a number of buffer studies, finding similar sediment and nutrient removal rates, in addition to removal of up to 50 percent of pesticides and up to 60 percent of studied pathogens.

Removal of turbidity and nutrients from overland flow is one important water quality benefit of buffers. Buffers also provide food and shelter for various species, corridors for traveling wildlife, and shade for aquatic creatures. Buffers provide some stability against in-channel erosion by minimizing freeze-thaw cycling, minimizing wet-dry cycling, and building a resistant matrix of roots and soil, among others.

Buffers appear in regulations throughout Minnesota, a testament to their importance to the public. These include the Minnesota Shoreland Ordinance (Minnesota Statutes Section 103F.301-103F.345, and Minnesota Rules Parts 6105.0010-6105.1700), Wild and Scenic River Ordinance (Minnesota Statutes, Section 103.F301-103F.345, and Minnesota Rules, Parts 6105.0010-6105.1700), Ditch Law (Minnesota Statutes Section 103E.005-103E.812), and Buffer Law (Laws of Minnesota 2016, Chapter 85), among others.

These laws help protect Minnesota's waters, and vibrant water-dependent economic interests, including a $13 billion tourism industry, $2.5 billion to $2.4 trillion fishing industry, $11.6 billion camping, canoeing and hiking industry, $885 million water technology wages, and millions or more in residential property value, bridge stability and soil productivity.

Minnesota’s water industry grew three times faster than the overall economy in the past decade, with its employees making 27 percent above the state average (EQB, 2015). Several of the world’s leading water industry companies are based here, as well as nationally-ranked universities and colleges (EQB, 2015).

Minnesotans value water quality, voting in the 2008 Clean Water, Land and Legacy Amendment, and supporting a variety of other aquatic regulations, grants and innovations designed to protect and restore its aquatic resources. With 40 percent of waters impaired, water quality improvement will require a much effort, and a water ethic, but Minnesotans are well-positioned to protect and restore this land of sky-blue waters.

Chapter 5: Conclusions and References

5.1. Overview of the Factors Influencing Stream Lateral Erosion Rates

Stream channels are constantly changing. They may change slowly and predictably, or rapidly in response to a disturbance. Disturbances can include channel dredging and wetland drainage for historical flood control efforts, watershed developments, and natural storm events. Channel erosion can contribute a significant percentage of a stream's sediment load. A restoration, or reduction of turbidity from channel sources, may be difficult due to the complexity of interactions between erosion rates, soils, geomorphology, chemistry, vegetation, hydrology and stream size.

5.2. Analyzing Lateral Erosion Measurement Tools

GIS-based lateral migration tools allow the measurement of erosion rates over large temporal and spatial scales. GIS can be used to measure erosion rates along an entire stream system without the travel, weather or safety concerns, and over any time period that aerial photography is available. Three GIS-based lateral migration tools were used on the three study streams, and the results of two were compared to BANCS erosion rates. BANCS erosion rates require field measurements, and therefore only capture the bank movements observed by the user; the number of sites and time span assessed is therefore more limited. However, being in the field allows the user to capture a great deal of information, such as rooting depth, rooting density, bank angles, precise plant species, and other data.

Generally, BANCS and UMN results were higher than GIS tools and DNR results. The GIS results may be lower because they take the movement of the entire stream into account, rather than focusing on only erosion. They may also trend lower because they average the rates over reach lengths. BANCS samples discrete sites and applies what could be unrepresentative erosion rates to the entire stream. While BANCS is a popular tool for resource managers, and the modified prediction graphs will make them more accurate, GIS should be considered as an alternative.

5.3. The Effects of Vegetation Type and Channel Characteristics on Stream Lateral Erosion Rates

There was no clear correlation between erosion rate and vegetation type in this study. Underhill's (2013) review of the same streams did not find a correlation between cover type and erosion rates either, but did find the rooting characteristics of grass may be the best erosion control in small reaches, shrub rooting characteristics in medium reaches, and tree rooting characteristics in large reaches.

The most influential erosion control may be on tight bends with high banks towards the mouth of Elm Creek, wide meanders on the Buffalo River, and tight bends with high banks towards the beginning of the Whitewater main stem. Given the mouth of the Elm and beginning of the Whitewater mainstem are larger stream reaches, the tight bends with high banks here may benefit most from tree cover.

5.4. Setting Priorities in Erosion Control: Values, Policies and Targeted Restoration

There is value in vegetated buffers along streams, regardless of the vegetation strata. A buffer as narrow as 1.5 meters (5 feet) can remove the majority of total suspended solids, and a large fraction of nutrients (UMN, 2011). Removal of turbidity and nutrients from overland flow is one important water quality benefit of buffers. Buffers also provide food and shelter for various species, corridors for traveling wildlife, and shade for aquatic creatures. Buffers provide some stability against in-channel erosion by minimizing freeze-thaw cycling, minimizing wet-dry cycling, and building a resistant matrix of roots and soil, among others.

Buffers appear in regulations throughout Minnesota, a testament to their importance to the public. These laws help protect Minnesota's waters, and vibrant water-dependent economic interests, including a $13 billion tourism industry, $2.5 billion to $2.4 trillion fishing industry, $11.6 billion camping, canoeing and hiking industry, $885 million water technology wages, and millions or more in residential property value, bridge stability and soil productivity.

Minnesotans value water quality, voting in the 2008 Clean Water, Land and Legacy Amendment, and supporting a variety of other aquatic regulations, grants and innovations designed to protect and restore its aquatic resources. With 40 percent of waters impaired, water quality improvement will require a much effort, and a water ethic, but Minnesotans are well positioned to protect and restore this land of sky-blue waters.

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Appendix

Erosion Rate (feet/year) by Reach From Study Area Start to Mouth			
Stream	**Elm**	**Buffalo**	**Whitewater**
Kilometers	172	132	29
Reaches	119	109	11
Erosion	1.71	1.46	1.83
	1.74	2.02	2.22
	1.54	1.86	2.90
	1.66	2.19	2.15
	1.40	2.17	1.97
	1.75	1.53	1.40
	1.70	0.80	1.08
	1.63	1.93	0.89
	1.13	1.26	1.34
	0.67	1.57	1.47
	1.24	1.46	0.66
	1.33	1.99	
	1.45	1.96	
	1.87	2.18	
	1.25	2.02	
	0.79	1.69	
	1.07	2.08	
	0.82	2.00	
	2.03	0.99	
	1.88	2.02	
	1.85	1.90	
	1.39	0.71	
	1.54	1.26	
	1.32	1.98	
	2.62	1.16	
	1.47	1.65	
	1.68	2.28	
	1.77	2.42	

1.57	2.45
1.54	1.89
0.75	1.31
1.06	2.47
0.80	2.44
0.70	1.35
0.93	1.51
1.70	0.77
1.17	1.69
1.28	1.54
0.99	2.24
0.89	3.04
0.85	3.70
1.13	4.14
0.65	2.28
0.86	2.49
0.59	1.61
0.82	1.67
1.61	2.07
1.35	1.83
0.96	1.46
2.49	1.64
2.58	1.68
0.73	1.60
1.79	2.02
1.91	0.90
1.76	1.45
1.76	1.49
1.99	1.34
1.53	1.66
1.90	1.18
0.80	2.00
1.42	2.47
1.33	2.71
1.45	1.53
1.78	1.88

1.31	3.64
1.37	1.76
2.32	1.54
1.32	2.03
1.09	1.47
1.46	1.42
1.14	1.77
1.83	2.19
2.86	2.39
0.64	2.22
1.43	1.41
1.73	1.60
3.12	0.69
1.07	1.69
1.00	2.67
0.98	2.11
1.29	1.95
1.48	2.20
2.12	1.20
3.28	2.30
1.53	1.29
1.86	2.14
1.64	1.08
1.56	1.76
1.32	1.76
1.52	1.46
1.19	2.79
1.08	1.51
1.65	2.38
2.06	1.93
1.80	2.40
1.94	1.35
2.28	1.66
2.23	2.52
3.03	2.18
1.14	1.43

	2.67	2.08
	1.43	2.26
	1.14	3.02
	1.71	2.35
	1.14	2.76
	0.81	1.82
	1.38	1.70
	2.29	1.86
	3.07	1.54
	3.97	
	1.59	
	1.80	
	3.68	
	2.19	
	1.20	
	1.53	
	1.23	
	1.54	